



Life Cycle Cost Modeling of High-Speed Commercial Aircraft

Final Review – Trade Study Details

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Agenda

8:00 – 9:00	Executive Summary	John Olds
9:00 – 10:00	AnyLogic Model Development	Ami Patel
10:00 – 10:15	Break	
10:15 – 11:30	Trade Study Details	Hayden Magill
11:30 – 12:00	Data Exploration and Discussion	Mark Schaffer



Interim Review Recap

Current Study Objectives

Based on the 2021 study findings, the objectives for the current effort were:

1. Improve ROSETTA optimization methods and refine aircraft performance, cost, and business modeling
2. Further characterize business case viability in the Mach 2-5, 20-50 passenger, 3500-7000 nmi design space
 - Develop baseball cards with details on individual point designs in this space
3. Explore alternative scenarios
 - Consider alternative fuels to Jet-A: sustainable aviation fuel (SAF), liquified natural gas (LNG), and liquified hydrogen (LH2)
 - Consider allowing the airline operator to have a mixed fleet of short-range and long-range aircraft
 - Evaluate the impact of allowing overland routes over the continental United States
 - Assess the impact of delaying initial operating capability (IOC) date
4. Develop a Discrete Event Simulation (DES) to expand business modeling capabilities beyond the limitations of the Excel-based ROSETTA implementation
 - Improve the fidelity of the route-by-route and aircraft-by-aircraft modeling



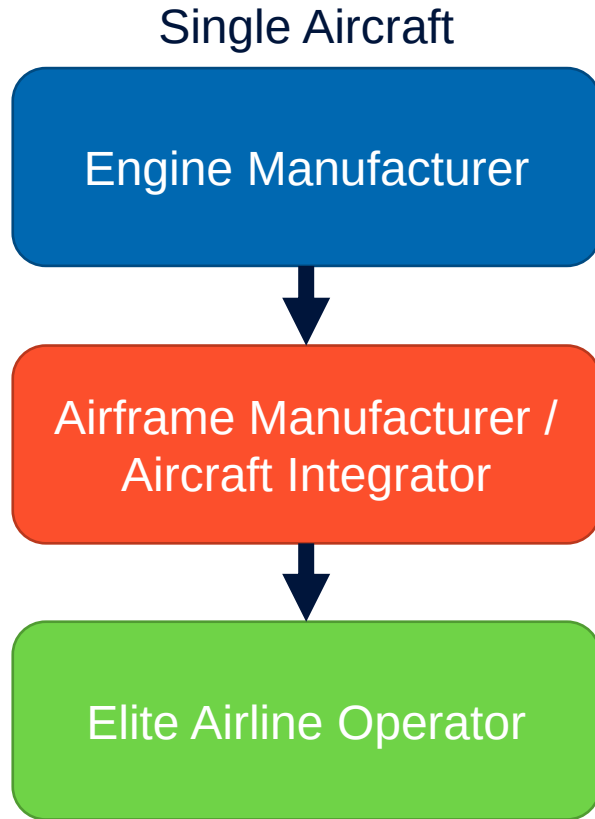
Methodology & Assumptions

Business Modeling Major Assumptions

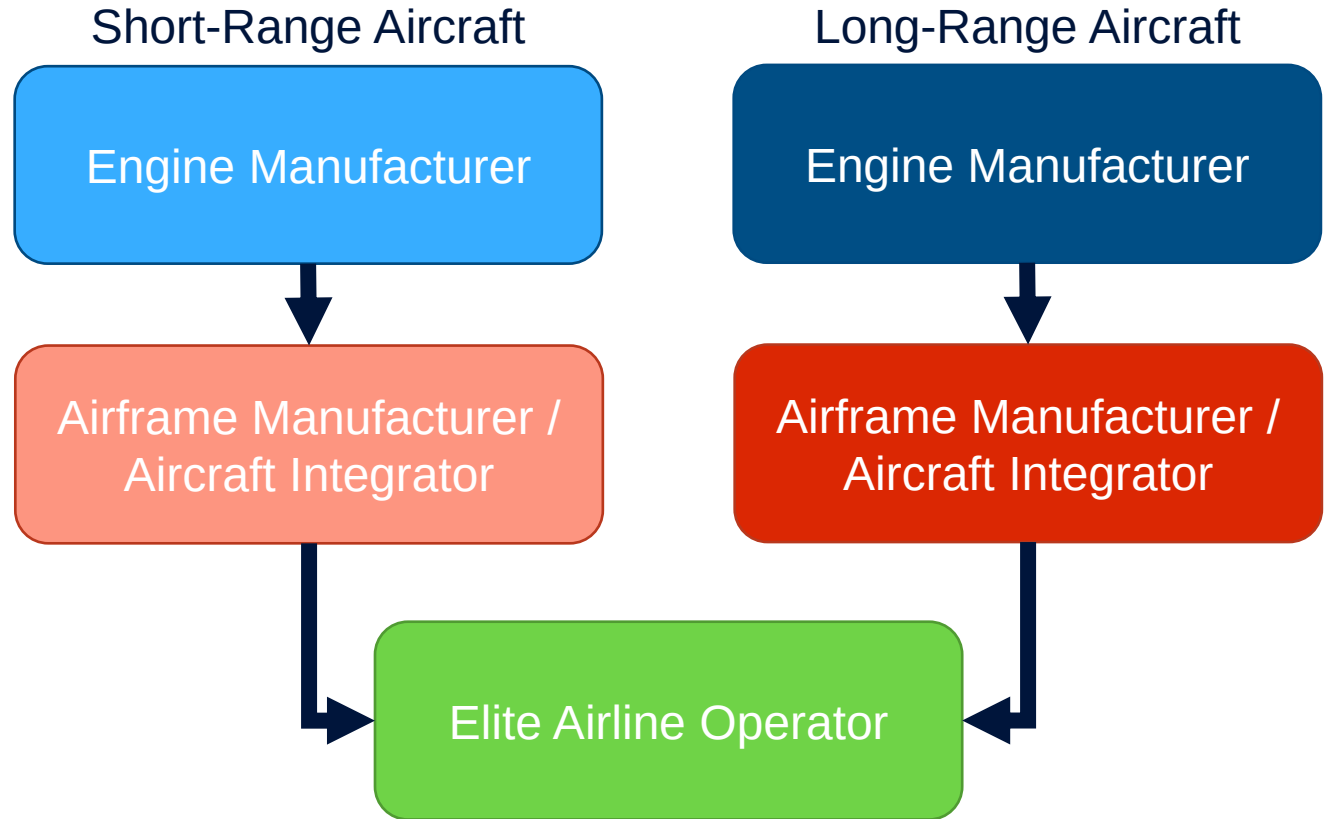
- ▶ **Candidate high-speed aircraft will be parametrically sized for a design range, passenger count, cruise Mach number and be configured to offer a single passenger-class service**
 - Mach 2 – Mach 5, 20 PAX – 50 PAX, 3000 nmi - 7000 nmi unrefueled range, Jet-A, SAF, LNG, or LH2
 - Mach number influences L/D, engine performance, thermal environment, turnaround times, flight times, TPS mass, etc.
 - Parametric non-recurring and production costs determined from meta-models created from Galorath SEER and other tools with 10-30% contingency applied
 - Ticket prices for each route determine daily passenger capture based on prior market elasticity research and reference subsonic demand on each route
- ▶ **Engine manufacturers, airframe manufacturers, and the elite airline operator have individual, but coupled, business cases that are each modeled with cash flow, revenue, expenses, learning curves, certification, etc. for each economic scenario**
- ▶ **“Captured” routes from the list of 90+ candidate transoceanic city pairs must be within the aircraft’s unrefueled range and have the demand for at least one flight per day**
- ▶ **Business cases are optimized based on the objective function to maximize IRR up to 25%, then maximize passenger participation**
- ▶ **Business models capture operations from 2022-2056**
 - To approximate COVID recovery, we expect market numbers to return to 2019 levels by 2024. After that, annual growth rates of 0.94%/year are assumed
 - United States Government purchases the first aircraft produced - regardless of size or speed - “anchor buy” concept establishes a minimum number of aircraft to be produced (max of 20 aircraft within \$5B budget)

Business Case Modeling

Single Aircraft Business Model



Mixed Fleet Business Model



For the Mixed Fleet Business Model, no heritage or synergies are assumed between manufacturers in order to generate a more conservative business case solution

HSCV Workshop Feedback

▤ Received vehicle modeling feedback from participants that we plan to address in the near term

- Aircraft OEW and costs lower than expected
- Aircraft takeoff thrust-to-weight may be too low to enable Mach 1 transition
- Concern about capability to close aircraft for design range above 5000 nmi

▤ Updated sizing assumptions:

- Increased mass growth allowance from 20% to 30%
- Increased engine ignition thrust-to-weight from 0.325 to 0.375
- Reduced supersonic lift-to-drag to 80% theoretical from Kuchemann equation
- Correct BFL calculation (incorrectly linked to theoretical S_{ref} instead of exposed S_{ref})

▤ Updated cost assumptions:

- Jet-A Fuel Price set to \$4.06 given recent price increases
- DDT&E for airframe and engine to be more aligned with industry estimates
- Fixed Operating Costs roughly doubled due to higher cost assumptions and accounting for pilot/crew flight hour limitations

Updates after HSCV Workshop

- ▶ Across most key metrics, values worsened relative to the data presented in Chicago
- ▶ IRR reflects change in objective function to achieve 25% IRR instead of 30%
- ▶ Costs reflect larger aircraft, increased fuel costs and other operating costs, and additional contingency on DDT&E
- ▶ These deltas reflect the most conservative changes that can be made to the model

Results for Mach 2, 4000 nmi, 50 pax aircraft

Metric	Before Workshop		After Workshop
OEW/MEW (lbm)	64,000	▲	74,000
MTOW (lbm)	137,000	▲	179,000
Single Engine Thrust (SL - lbf)	11,200	▲	16,800
BFL (ft)	5,100	▲	7,900
Emissions (kg/km/pax)	0.24	▲	0.36
DDT&E (Airframe/Engine)	\$2.8B / \$1.4B	▲	\$3.7B / \$2.2B
TFU (Airframe/Engine)	\$81M / \$7.3M	▲	\$84M / \$11.0M
Ticket Price	\$2,080	▲	\$3,970
Passengers per Year	3.6M	▼	1.8M
Routes Captured	28	▼	23
Aircraft Price	\$180M	▲	\$330M
Single Engine Price	\$12.6M	▲	\$27.5M
Aircraft Sold	379	▼	151
Minimum IRR	30.2%	▼	25.0%
Max Exposure (Operator)	\$5.0B	-	\$5.0B

Comparison to Boom Projections

- ▶ Based on available public data
- ▶ Model Estimate still using Jet-A & makes assumptions about engines
 - Boom plans to use SAF & has not finalized engines to be used on Overture
 - Values may reflect these uncertainties

- ▶ Model Estimate is using 75 passengers for sizing based on Overture’s 65-88 passenger count
- ▶ Boom’s estimates for captured routes include overland & multi-leg trips and round-trip ticket prices

Metric	Boom Estimate		Model Estimate
DDT&E (Airframe/Engine)	\$6-8B	▲	\$5.8B / \$2.9B
Ticket Price	\$5,000	▲	\$6,500
Routes Captured	500*	▼	19**
Aircraft Price	\$200M	▲	\$640M
Aircraft Sold	1000	▼	90

* Overland and transoceanic routes

** Transoceanic routes only

Mixed Fleet Results

- ▶ Uses data from before HSCV Workshop feedback was implemented
 - Trends remain consistent, only magnitudes shift
- ▶ Mixed Fleet cases see improvement over a single aircraft case based on demand alone
- ▶ However, the demand is only marginally better and the long-range aircraft in the Mixed Fleet has significantly higher prices from the Operator and Manufacturers

Key Metrics	Best Mixed Fleet Case		Best Single Case
Mach	3	2	2.4
Range (nmi)	3900	5700	4100
Passengers	50	20	38
Ticket Price	\$1,925	\$7,330	\$2,064
Aircraft Price	\$198M	\$224	\$149M
Engine Price	\$15.9 M x4	\$18.9 M x4	\$11.2 M x4
Aircraft Sold	369	199	455
Market Capture	4,080,000	700,000	4,210,000
Total Captured	4,780,000		4,210,000



Alternative Fuels Trade Study

Objective

▶ Evaluate the economic performance of single aircraft and mixed fleet business cases for alternative fuel types

- Synthetic/Sustainable Aviation Fuel (SAF)
- Liquid Natural Gas or Methane (LNG)
- Liquid Hydrogen (LH2)

▶ The main objective was to determine if alternative fuels generated more favorable business cases due to differences in fuel properties

▶ For the trade matrices, short-range aircraft were set to 4000 nmi design range, and long-range aircraft design range varied with Mach number

- Long-range aircraft become infeasible at higher Mach regimes

Case	Range	PAX	Cruise Mach	Fuel Type
Baseline-A	Short	Best	Best	Varies
Baseline-B	Long	Best	Best	Varies
1	Short	20	2	Varies
2	Short	20	3	Varies
3	Short	20	4	Varies
4	Short	20	5	Varies
5	Short	50	2	Varies
6	Short	50	3	Varies
7	Short	50	4	Varies
8	Short	50	5	Varies
9	Long	20	2	Varies
10	Long	20	3	Varies
11	Long	20	4	Varies
12	Long	20	5	Varies
13	Long	50	2	Varies
14	Long	50	3	Varies
15	Long	50	4	Varies
16	Long	50	5	Varies

Process

- ▶ **Taking the existing Mixed Fleet ROSETTA Model, fundamental fuel properties were added to the model for each alternative fuel**
 - A Fuel Type input was added, and the corresponding fuel properties and assumptions were used for sizing, performance, and economic calculations
 - Fuel cost calculations were slightly modified to reflect anticipated changes in fuel prices over time based

- ▶ **Given SAF's density is roughly the same as Jet-A, no sizing adjustments were made**

- ▶ **For LNG & LH2, sizing adjustments were made to reflect the cryogenic needs of the fuels**
 - LNG & LH2 propellants are stored in pressurized, insulated, cylindrical tanks in the fuselage
 - LH2 planes required multiple side-by-side tanks in the fuselage to maintain reasonable fuselage lengths

- ▶ **Results were consolidated and analyzed to identify trends and evaluate business case metrics**
 - The objective function drove cases to reach a minimum IRR of 25% and then maximize demand once that was achieved
 - Cases with aircraft MTOW greater than 1M lbm and/or achieving less than 0% IRR were removed from analysis
 - Ticket Price, Captured Demand, Aircraft Price, & Aircraft Sold were all used to check the robustness of a business case
 - Generally, lower ticket prices and higher demand/production were viewed as more robust business case since these cases were less sensitive to model input changes

Major Fuel Assumptions

PROPERTY	JET-A	SAF (100%)	LNG	LH2
Density (lb/gal)	6.66	6.58	3.91	0.55
Storage Temp	-40°C	-40°C	-163°C	-249°C
Supersonic Isp* (s)	3000	3060	3470	7200
Price	\$4.06/gal	\$6.70/gal	\$1.30/gal	\$3.60/gal
DDT&E Impact	0% Inc.	2.5% Inc.	30% Inc.	60% Inc
TFU Impact	0% Inc.	2.5% Inc.	5% Inc.	10% Inc.

*Supersonic Isp for Mach 2 aircraft



All fuels will have their respective Fuel Price k-factor applied to reflect the anticipated change of prices over time. Fuel supply is also assumed to be sufficient.

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
Best – SR	4,000	2.01	40	25.0%	\$3,900	4.6%	197	\$250M	\$19.8M	143,000	59,300	13,400	0.34
Best – LR	5,700	2.00	38	25.0%	\$5,200	5.8%	300	\$250M	\$19.8M	222,000	77,000	20,900	0.49
1	4,000	2.0	20	25.1%	\$5,000	3.7%	289	\$170M	\$13.5M	95,000	40,200	8,900	0.47
2	4,000	3.0		25.5%	\$7,000	2.8%	207	\$260M	\$23.4M	135,000	51,600	12,700	0.75
3	4,000	4.0		25.0%	\$10,000	1.9%	152	\$380M	\$37.1M	161,000	60,900	15,100	0.92
4	4,000	5.0		25.2%	\$12,700	1.5%	123	\$450M	\$50.0M	186,000	71,600	17,500	1.06
5	4,000	2.0	50	25.0%	\$4,300	4.1%	143	\$350M	\$27.8M	167,000	69,000	15,700	0.33
6	4,000	3.0		25.1%	\$5,700	3.4%	111	\$470M	\$43.1M	236,000	87,700	22,100	0.53
7	4,000	4.0		24.9%	\$11,500	1.5%	53	\$990M	\$97.6M	276,000	101,900	25,900	0.63
8	4,000	5.0		23.7%	\$11,500	1.6%	61	\$980M	\$105.2M	313,000	117,400	29,300	0.71
9	6,100	2.0	20	25.0%	\$8,200	3.4%	324	\$210M	\$17.0M	179,000	60,300	16,800	0.72
10	5,700	3.0		22.1%	\$13,100	2.0%	188	\$370M	\$34.9M	317,000	96,500	29,700	1.48
11	5,400	4.0		19.0%	\$15,500	1.1%	101	\$520M	\$57.0M	382,000	118,700	35,800	1.87
12	5,000	5.0		18.4%	\$15,000	1.4%	120	\$480M	\$58.5M	381,000	126,000	35,700	1.96
13	6,100	2.0	50	25.0%	\$8,300	2.9%	131	\$530M	\$41.9M	315,000	103,800	29,500	0.51
14	5,700	3.0		21.3%	\$11,600	2.0%	81	\$850M	\$77.5M	545,000	163,500	51,100	1.02
15	5,400	4.0		18.6%	\$11,600	2.0%	81	\$870M	\$90.8M	635,000	194,500	59,500	1.24
16	5,000	5.0		18.4%	\$12,200	1.9%	74	\$950M	\$108.5M	616,000	200,400	57,700	1.26

Jet-A Matrix – Best Short-Range

ID: JTA.M2.01.P40.R4000.20220810



Mach 2.01
Cruise Speed



4,000 nmi
Max Range



40
Passenger Count



JetA
Fuel Type

COST METRICS (FY21 USD)

DDT&E

\$3.4B
Airframe

\$2.0B
Engine

TFU

\$85M
Airframe

\$9.7M
Engine

ENVIRONMENTAL METRICS

91 EPNdB

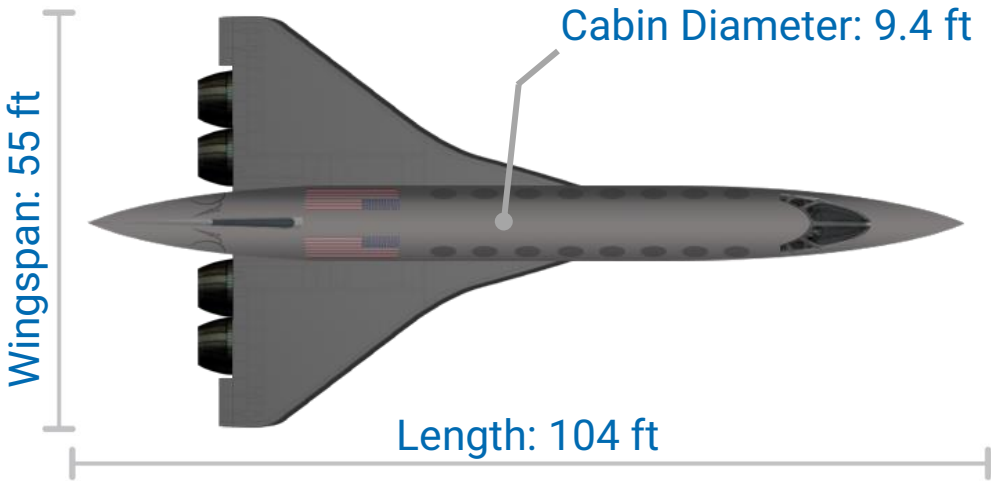
Lateral Takeoff Noise

0.34 kg/km/pax
Emissions (CO₂e)

104 PNLdB

Sonic Boom

0.11 kg/km/pax
Fuel Consumption Rate



143,000 lbm
MTOW

59,300 lbm
MEW

4 x 13,400 lbf
Engine Thrust SLS

4.3 hours
Gate-to-Gate Time
at Max Range

56,600 ft
Cruise Altitude

6,600 ft
Bal. Field Length SL

AIRCRAFT NOTES

- Supersonic cruise condition L/D = 8
- Supersonic cruise condition Isp = 2978 s
- Vehicle propellant mass fraction (PMF) = 0.47
- Takeoff T/W = 0.375

Jet-A Matrix – Best Short-Range



ID: JTA.M2.01.P40.R4000.20220810

Key Inputs

**Mach 2.01**
Cruise Speed

**4,000 nmi**
Range

**40**
Passenger Count

**JetA**
Fuel Type

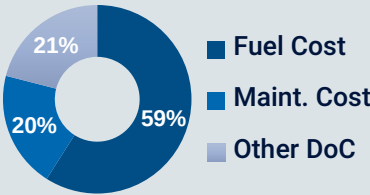


OPERATOR METRICS

\$3,900-\$4,400
Ticket Price

1.8M
Pax/Year

24
Routes Captured



MANUFACTURER METRICS

\$251M
Aircraft Price

\$172M
Airframe Price

\$20M x4
Engine Price

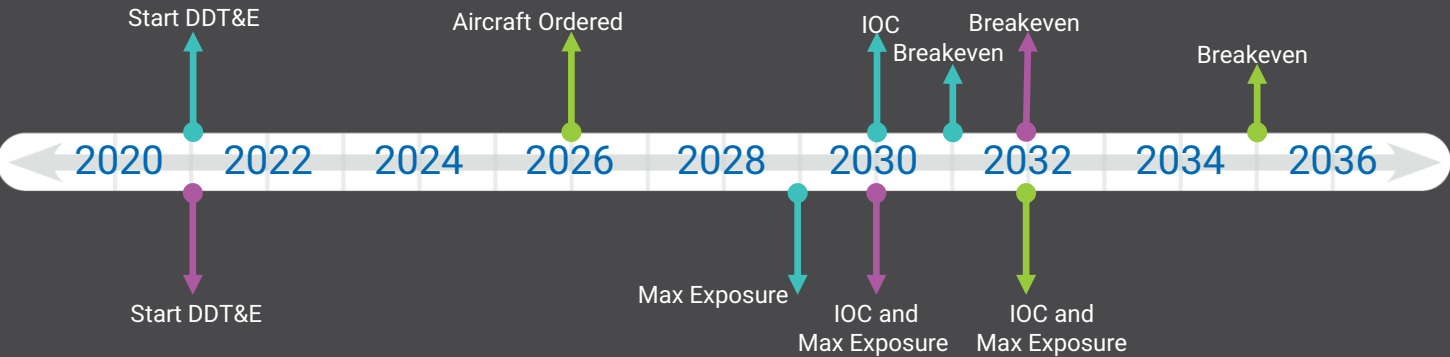
197
Aircraft Sold

KEY EVENTS & DATES

● OPERATOR

● ENGINE MANUFACTURER

● AIRFRAME MANUFACTURER



BUSINESS CASE ANALYSIS

This aircraft is capturing 24 of 37 addressable routes that are within its design range which are exclusively Atlantic Ocean routes. Good business case with reasonable ticket prices and aircraft prices that generates decent demand capture. Max exposures are also within reason.

Business Results

OPERATOR

25%
IRR

\$2.4B
NPV

\$4.9B
Max Exposure

ENGINE MANUFACTURER

25%
IRR

\$927M
NPV

\$1.3B
Max Exposure

AIRFRAME MANUFACTURER

25%
IRR

\$2.0B
NPV

\$2.9B
Max Exposure

Jet-A Matrix – Best Long-Range

ID: JTA.M2.00.P38.R5700.20220810



Mach 2
Cruise Speed



5,700 nmi
Max Range



38
Passenger Count



JetA
Fuel Type

COST METRICS (FY21 USD)

DDT&E

\$4.1B
Airframe

\$2.3B
Engine

TFU

\$109M
Airframe

\$15M
Engine

ENVIRONMENTAL METRICS

92 EPNdB

Lateral Takeoff Noise

0.49 kg/km/pax

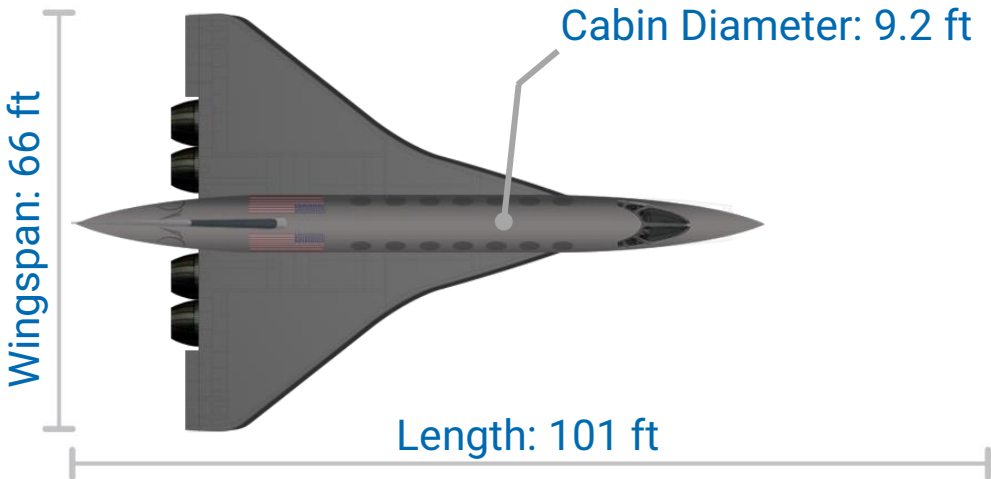
Emissions (CO₂e)

105 PNLdB

Sonic Boom

0.15 kg/km/pax

Fuel Consumption Rate



222,000 lbm
MTOW

77,000 lbm
MEW

4 x 20,900 lbf
Engine Thrust SLS

5.8 hours
Gate-to-Gate Time
at Max Range

56,400 ft
Cruise Altitude

6,600 ft
Bal. Field Length SL

AIRCRAFT NOTES

- Supersonic cruise condition L/D = 8
- Supersonic cruise condition Isp = 2996 s
- Vehicle propellant mass fraction (PMF) = 0.47
- Takeoff T/W = 0.375

Jet-A Matrix – Best Long-Range



ID: JTA.M2.00.P38.R5700.20220810

Key Inputs

Mach 2
Cruise Speed

5,700 nmi
Range

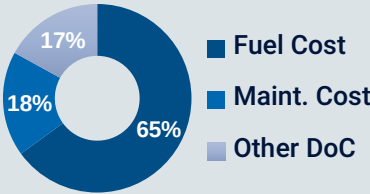
38
Passenger Count

JetA
Fuel Type



OPERATOR METRICS

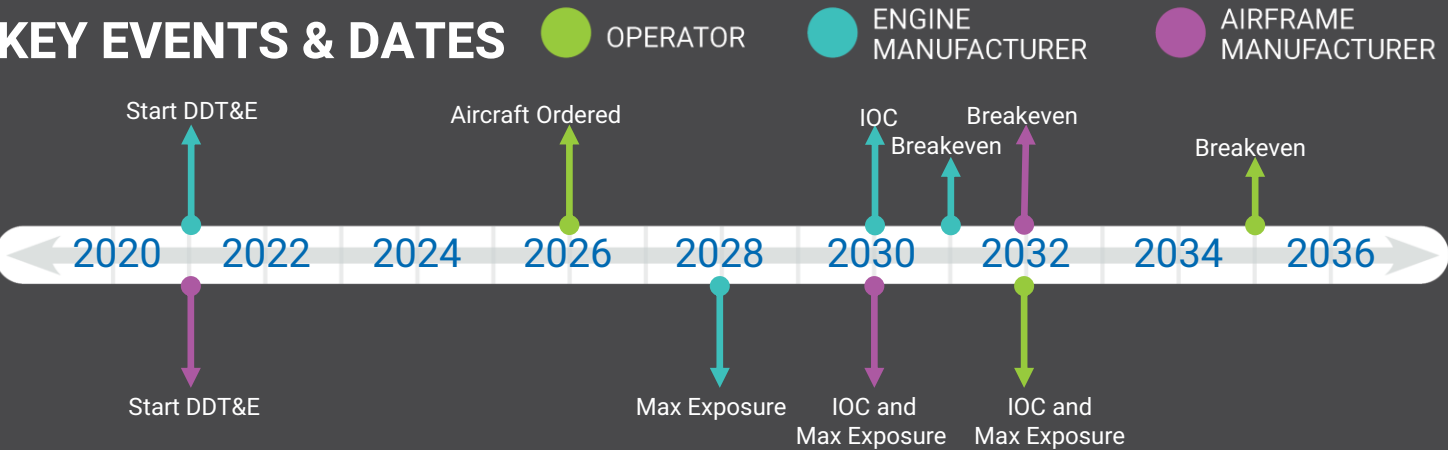
\$5,200-\$6,700 **2.3M** **49**
Ticket Price Pax/Year Routes Captured



MANUFACTURER METRICS

\$251M **\$172M** **\$20M x4** **300**
Aircraft Price Airframe Price Engine Price Aircraft Sold

KEY EVENTS & DATES



BUSINESS CASE ANALYSIS

This aircraft is capturing 49 of 78 addressable routes that are within its design range which are exclusively Atlantic Ocean routes. Since the aircraft is more passenger efficient, ticket prices don't become overly expensive, enabling higher demand capture overall.

Business Results

OPERATOR
25% **\$3.5B** **\$7.2B**
IRR NPV Max Exposure

ENGINE MANUFACTURER
25% **\$1.0B** **\$1.2B**
IRR NPV Max Exposure

AIRFRAME MANUFACTURER
25% **\$2.1B** **\$2.9B**
IRR NPV Max Exposure

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
Best – SR	4,000	2.01	38	25.1%	\$4,200	4.3%	200	\$240M	\$19.3M	135,000	56,500	12,600	0.34
Best – LR	5,700	2.00	50	25.0%	\$5,500	5.3%	212	\$330M	\$26.8M	263,000	91,600	24,600	0.43
1	4,000	2.0	20	25.0%	\$5,100	3.7%	298	\$170M	\$14.7M	92,000	39,700	8,700	0.45
2	4,000	3.0		25.0%	\$7,100	2.7%	200	\$250M	\$22.6M	130,000	50,400	12,200	0.72
3	4,000	4.0		25.2%	\$12,200	1.5%	120	\$440M	\$49.4M	154,000	59,300	14,500	0.87
4	4,000	5.0		25.1%	\$12,800	1.5%	120	\$440M	\$49.0M	178,000	69,500	16,700	1.00
5	4,000	2.0	50	25.0%	\$4,800	3.7%	131	\$380M	\$30.3M	163,000	68,000	15,300	0.32
6	4,000	3.0		25.0%	\$6,900	2.6%	93	\$540M	\$49.9M	227,000	85,700	21,300	0.50
7	4,000	4.0		24.5%	\$11,500	1.5%	54	\$970M	\$96.3M	265,000	99,200	24,800	0.60
8	4,000	5.0		23.5%	\$11,500	1.6%	61	\$950M	\$104.1M	299,000	114,000	28,100	0.67
9	6,100	2.0	20	25.0%	\$8,500	3.3%	314	\$210M	\$17.2M	170,000	58,300	16,000	0.68
10	5,700	3.0		22.5%	\$15,400	1.2%	122	\$420M	\$41.7M	292,000	90,300	27,300	1.34
11	5,400	4.0		19.4%	\$15,500	1.1%	101	\$490M	\$54.8M	347,000	109,700	32,500	1.68
12	5,000	5.0		18.4%	\$15,000	1.4%	119	\$460M	\$56.6M	348,000	117,100	32,700	1.77
13	6,100	2.0	50	25.0%	\$8,500	2.8%	129	\$530M	\$42.3M	299,000	100,300	28,100	0.48
14	5,700	3.0		21.3%	\$11,600	2.0%	80	\$810M	\$75.9M	502,000	153,000	47,100	0.93
15	5,400	4.0		18.6%	\$12,200	1.8%	71	\$900M	\$94.9M	579,000	180,300	54,300	1.12
16	5,000	5.0		18.3%	\$12,400	1.8%	69	\$950M	\$109.8M	566,000	187,100	53,000	1.15

SAF Matrix – Best Short-Range

ID: SAF.M2.01.P38.R4000.20220810



Mach 2.01
Cruise Speed



4,000 nmi
Max Range



38
Passenger Count



SAF
Fuel Type

COST METRICS (FY21 USD)

DDT&E

\$3.3B
Airframe

\$2.0B
Engine

TFU

\$81M
Airframe

\$9.3M
Engine

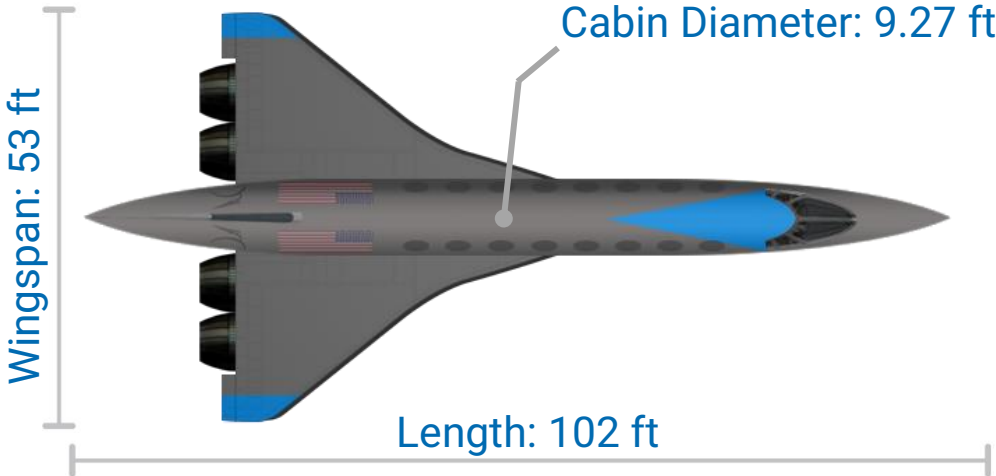
ENVIRONMENTAL METRICS

91 EPNdB
Lateral Takeoff Noise

104 PNLdB
Sonic Boom

0.34 kg/km/pax
Emissions (CO2e)

0.1 kg/km/pax
Fuel Consumption Rate



135,000 lbm MTOW	56,500 lbm MEW	4 x 12,600 lbf Engine Thrust SLS
4.3 hours Gate-to-Gate Time at Max Range	56,500 ft Cruise Altitude	6,600 ft Bal. Field Length SL

AIRCRAFT NOTES

- Supersonic cruise condition L/D = 8
- Supersonic cruise condition Isp = 3048 s
- Vehicle propellant mass fraction (PMF) = 0.47
- Takeoff T/W = 0.375

SAF Matrix – Best Short-Range



ID: SAF.M2.01.P38.R4000.20220810

Key Inputs

**Mach 2.01**
Cruise Speed

**4,000 nmi**
Range

**38**
Passenger Count

**SAF**
Fuel Type

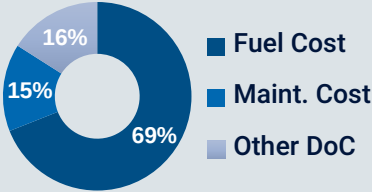


OPERATOR METRICS

\$4,200-\$4,700
Ticket Price

1.7M
Pax/Year

24
Routes Captured



MANUFACTURER METRICS

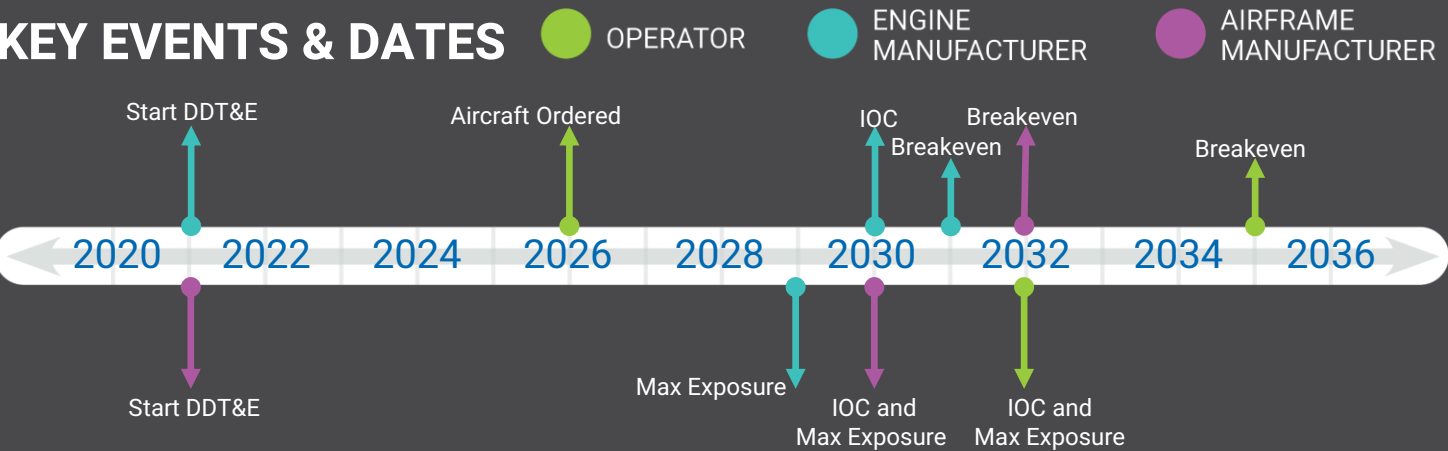
\$239M
Aircraft Price

\$161M
Airframe Price

\$19M x4
Engine Price

200
Aircraft Sold

KEY EVENTS & DATES



BUSINESS CASE ANALYSIS

This aircraft is capturing 24 of 37 addressable routes that are within its design range which are exclusively Atlantic Ocean routes. Very similar to the Jet-A best cases but with a higher fuel cost, ticket price needs to compensate for the additional costs to be viable.

Business Results

OPERATOR
25% IRR
\$2.5B NPV
\$4.7B Max Exposure

ENGINE MANUFACTURER
25% IRR
\$953M NPV
\$1.3B Max Exposure

AIRFRAME MANUFACTURER
25% IRR
\$2.0B NPV
\$2.9B Max Exposure

SAF Matrix – Best Long-Range



ID: SAF.M2.00.P50.R5700.20220810



Mach 2
Cruise Speed



5,700 nmi
Max Range



50
Passenger Count



SAF
Fuel Type

COST METRICS (FY21 USD)

DDT&E

\$4.6B
Airframe

\$2.5B
Engine

TFU

\$126M
Airframe

\$18M
Engine

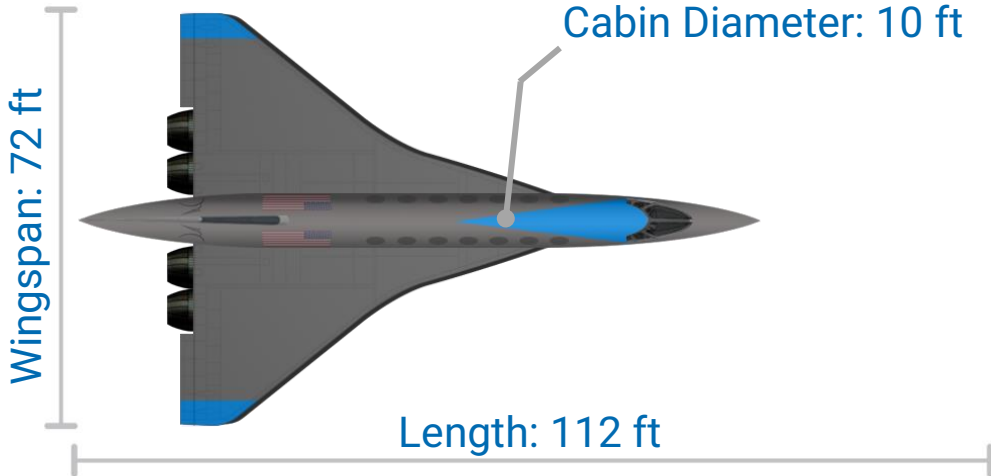
ENVIRONMENTAL METRICS

93 EPNdB
Lateral Takeoff Noise

105 PNLdB
Sonic Boom

0.43 kg/km/pax
Emissions (CO2e)

0.13 kg/km/pax
Fuel Consumption Rate



263,000 lbm MTOW	91,600 lbm MEW	4 x 24,600 lbf Engine Thrust SLS
5.8 hours Gate-to-Gate Time at Max Range	56,400 ft Cruise Altitude	6,600 ft Bal. Field Length SL

AIRCRAFT NOTES

- Supersonic cruise condition L/D = 8
- Supersonic cruise condition Isp = 3059 s
- Vehicle propellant mass fraction (PMF) = 0.47
- Takeoff T/W = 0.375

SAF Matrix – Best Long-Range



ID: SAF.M2.00.P50.R5700.20220810

Key Inputs

**Mach 2**
Cruise Speed

**5,700 nmi**
Range

**50**
Passenger Count

**SAF**
Fuel Type

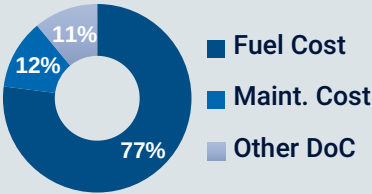


OPERATOR METRICS

\$5,500-\$7,000
Ticket Price

2.1M
Pax/Year

42
Routes Captured



MANUFACTURER METRICS

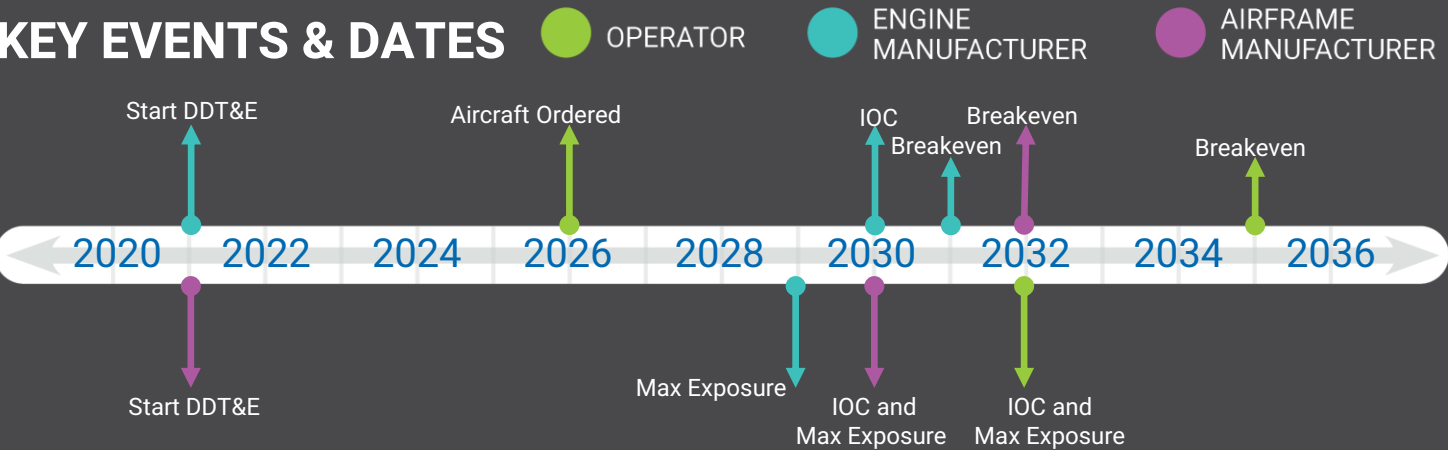
\$332M
Aircraft Price

\$224M
Airframe Price

\$27M x4
Engine Price

212
Aircraft Sold

KEY EVENTS & DATES



BUSINESS CASE ANALYSIS

This aircraft is capturing 42 of 78 addressable routes that are within its design range which are exclusively Atlantic Ocean routes. Longer ranges result in higher fuel costs so increased ticket prices reduce demand and force the manufacturers to charge more to compensate for lower production.

Business Results

OPERATOR

25%
IRR

\$3.9B
NPV

\$7.1B
Max Exposure

ENGINE MANUFACTURER

25%
IRR

\$1.2B
NPV

\$1.5B
Max Exposure

AIRFRAME MANUFACTURER

25%
IRR

\$2.6B
NPV

\$3.8B
Max Exposure

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
Best – SR	4,000	2.41	39	25.0%	\$3,500	5.4%	204	\$310M	\$27.9M	170,000	72,700	16,000	0.38
Best – LR	5,700	2.00	39	25.1%	\$4,900	6.2%	309	\$310M	\$25.7M	258,000	98,700	24,200	0.45
1	4,000	2.0	20	25.0%	\$3,900	4.8%	374	\$160M	\$13.8M	99,000	45,200	9,300	0.40
2	4,000	3.0		25.1%	\$5,300	4.0%	295	\$240M	\$23.0M	143,000	59,300	13,400	0.67
3	4,000	4.0		25.1%	\$7,200	2.9%	214	\$330M	\$36.2M	167,000	68,500	15,600	0.80
4	4,000	5.0		25.4%	\$12,600	1.5%	126	\$530M	\$66.2M	187,000	77,700	17,600	0.90
5	4,000	2.0	50	25.0%	\$3,700	4.8%	165	\$360M	\$31.5M	175,000	77,700	16,400	0.29
6	4,000	3.0		25.0%	\$5,200	3.8%	126	\$500M	\$50.7M	251,000	101,900	23,500	0.47
7	4,000	4.0		24.6%	\$6,400	3.2%	106	\$650M	\$71.7M	290,000	117,000	27,200	0.55
8	4,000	5.0		23.5%	\$10,400	1.8%	69	\$990M	\$117.0M	323,000	131,800	30,300	0.62
9	6,100	2.0	20	25.0%	\$7,300	4.1%	381	\$240M	\$20.0M	207,000	77,400	19,400	0.70
10	5,700	3.0		21.9%	\$15,200	1.3%	126	\$560M	\$57.6M	405,000	137,900	38,000	1.59
11	5,400	4.0		20.2%	\$14,700	1.4%	128	\$600M	\$69.1M	457,000	157,800	42,900	1.89
12	5,000	5.0		20.8%	\$15,000	1.4%	119	\$640M	\$80.7M	406,000	147,300	38,100	1.76
13	6,100	2.0	50	25.4%	\$8,800	2.7%	128	\$630M	\$59.1M	364,000	133,900	34,100	0.49
14	5,700	3.0		19.7%	\$11,000	2.2%	94	\$940M	\$91.5M	709,000	239,300	66,500	1.11
15	5,400	4.0		17.9%	\$11,300	2.1%	88	\$1.0B	\$116.5M	795,000	272,100	74,500	1.31
16	5,000	5.0		18.8%	\$11,500	2.1%	81	\$1.1B	\$137.0M	700,000	251,600	65,700	1.21

LNG Matrix – Best Short-Range



ID: LNG.M2.41.P39.R4000.20220810

Mach 2.41
Cruise Speed

4,000 nmi
Max Range

39
Passenger Count

LNG
Fuel Type

COST METRICS (FY21 USD)

DDT&E

\$3.9B

Airframe

\$2.9B

Engine

TFU

\$100M

Airframe

\$14M

Engine

ENVIRONMENTAL METRICS

91 EPNdB

Lateral Takeoff Noise

103 PNLdB

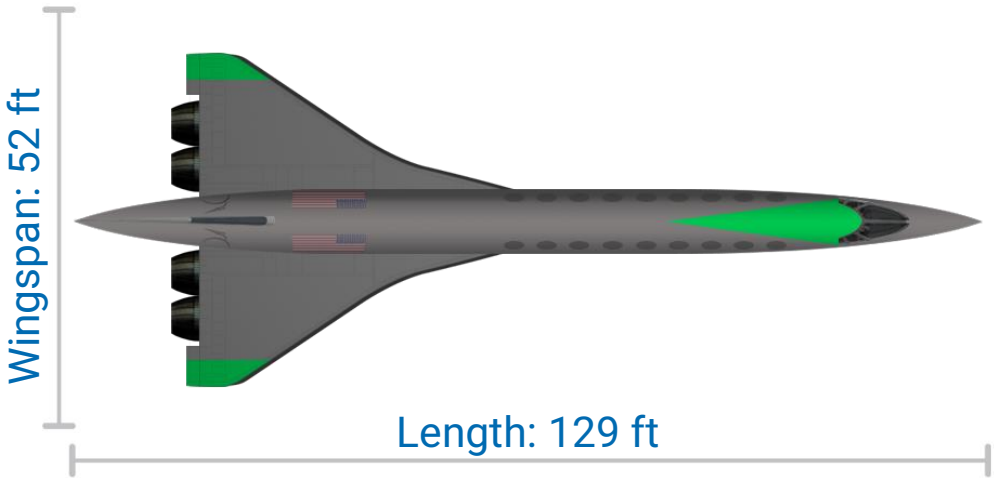
Sonic Boom

0.38 kg/km/pax

Emissions (CO₂e)

0.13 kg/km/pax

Fuel Consumption Rate



170,000 lbm

MTOW

72,700 lbm

MEW

4 x 16,000 lbf

Engine Thrust SLS

3.7 hours

Gate-to-Gate Time
at Max Range

64,100 ft

Cruise Altitude

7,700 ft

Bal. Field Length SL

AIRCRAFT NOTES

- Supersonic cruise condition L/D = 6.7
- Supersonic cruise condition Isp = 2851 s
- Vehicle propellant mass fraction (PMF) = 0.47
- Takeoff T/W = 0.375

LNG Matrix – Best Short-Range



ID: LNG.M2.41.P39.R4000.20220810

Key Inputs

**Mach 2.41**
Cruise Speed

**4,000 nmi**
Range

**39**
Passenger Count

**LNG**
Fuel Type

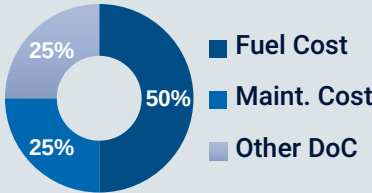


OPERATOR METRICS

\$3,500-\$4,000
Ticket Price

2.1M
Pax/Year

27
Routes Captured



MANUFACTURER METRICS

\$305M
Aircraft Price

\$194M
Airframe Price

\$28M x4
Engine Price

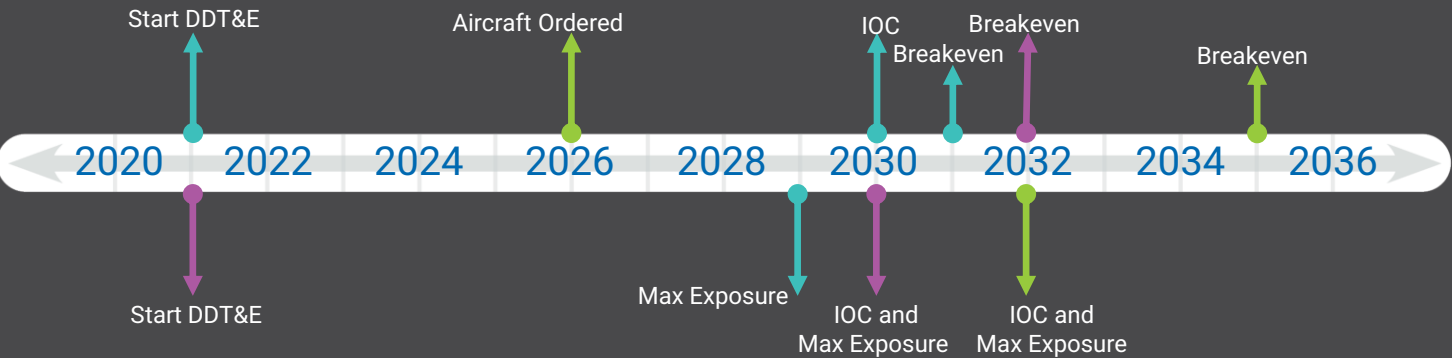
204
Aircraft Sold

KEY EVENTS & DATES

● OPERATOR

● ENGINE MANUFACTURER

● AIRFRAME MANUFACTURER



BUSINESS CASE ANALYSIS

This aircraft is capturing 27 of 37 addressable routes that are within its design range which are exclusively Atlantic Ocean routes. Cryogenic tanks drive up aircraft prices, but reduced fuel costs enable lower ticket prices & a faster aircraft to capture more demand.

Business Results

OPERATOR

25%
IRR

\$3.1B
NPV

\$6.4B
Max Exposure

ENGINE MANUFACTURER

25%
IRR

\$1.3B
NPV

\$2.0B
Max Exposure

AIRFRAME MANUFACTURER

25%
IRR

\$2.4B
NPV

\$3.4B
Max Exposure

LNG Matrix – Best Long-Range



ID: LNG.M2.00.P39.R5700.20220810



Mach 2
Cruise Speed



5,700 nmi
Max Range



39
Passenger Count



LNG
Fuel Type

COST METRICS (FY21 USD)

DDT&E

\$4.8B
Airframe

\$3.2B
Engine

TFU

\$132M
Airframe

\$18M
Engine

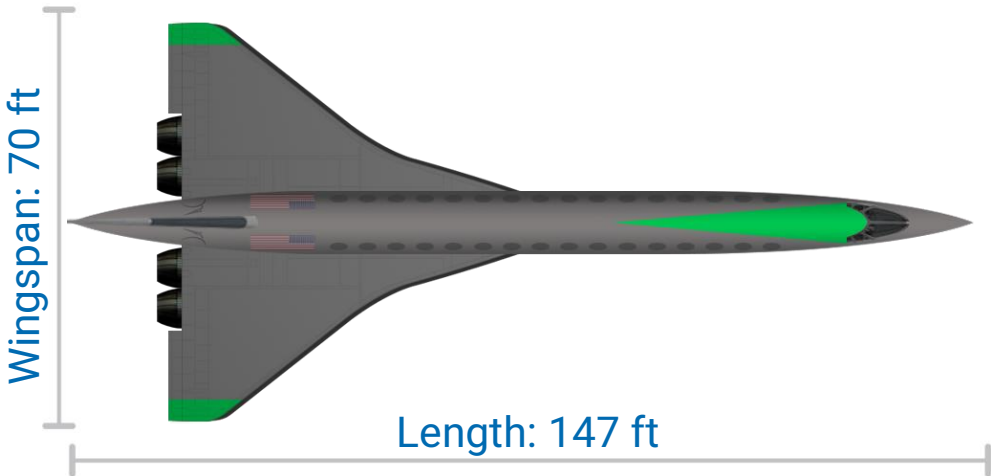
ENVIRONMENTAL METRICS

93 EPNdB
Lateral Takeoff Noise

105 PNLdB
Sonic Boom

0.45 kg/km/pax
Emissions (CO2e)

0.16 kg/km/pax
Fuel Consumption Rate



258,000 lbm MTOW	98,700 lbm MEW	4 x 24,200 lbf Engine Thrust SLS
5.8 hours Gate-to-Gate Time at Max Range	56,400 ft Cruise Altitude	7,100 ft Bal. Field Length SL

AIRCRAFT NOTES

- Supersonic cruise condition L/D = 7.5
- Supersonic cruise condition Isp = 3459 s
- Vehicle propellant mass fraction (PMF) = 0.47
- Takeoff T/W = 0.375

LNG Matrix – Best Long-Range



ID: LNG.M2.00.P39.R5700.20220810

Key Inputs

Mach 2
Cruise Speed

5,700 nmi
Range

39
Passenger Count

LNG
Fuel Type

OPERATOR METRICS

\$4,900-\$6,300
Ticket Price

2.5M
Pax/Year

50
Routes Captured

Cost Breakdown

25%
Fuel Cost

59%
Maint. Cost

16%
Other DoC

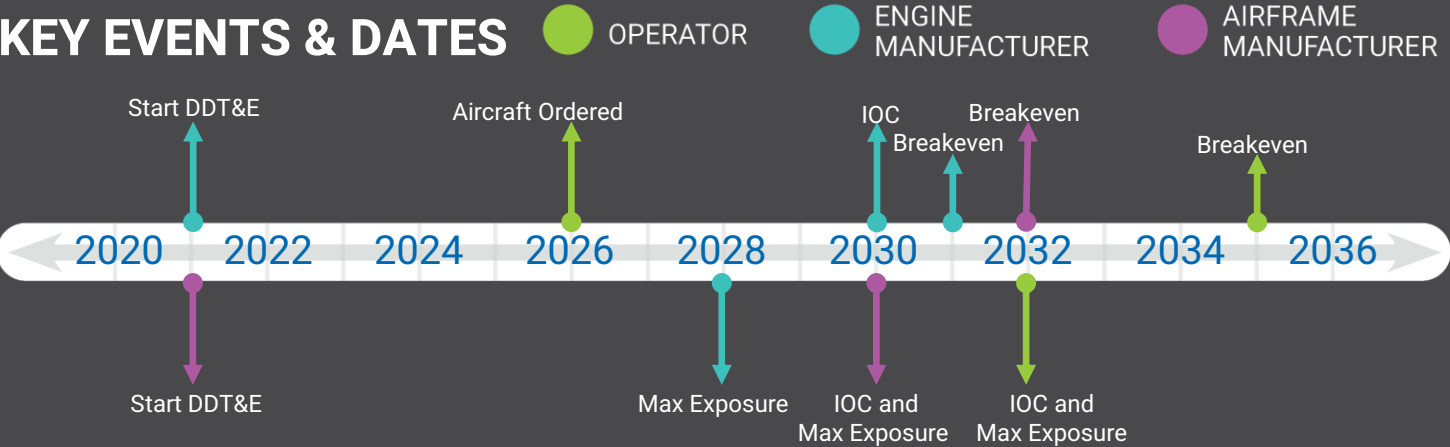
MANUFACTURER METRICS

\$306M
Aircraft Price

\$203M
Airframe Price

\$26M x4
Engine Price

309
Aircraft Sold



BUSINESS CASE ANALYSIS

This aircraft is capturing 50 of 78 addressable routes that are within its design range which are exclusively Atlantic Ocean routes. With additional route capture and the ability to keep ticket prices lower due to fuel cost, this case captures the most demand.

Business Results

OPERATOR

25%
IRR

\$4.9B
NPV

\$9.1B
Max Exposure

ENGINE MANUFACTURER

25%
IRR

\$1.3B
NPV

\$1.8B
Max Exposure

AIRFRAME MANUFACTURER

25%
IRR

\$2.6B
NPV

\$3.3B
Max Exposure

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
Best – SR	4,000	2.28	30	19.0%	\$10,300	1.6%	112	\$270M	\$28.1M	116,000	72,200	10,900	1.11E-03
Best – LR	5,700	2.00	38	17.2%	\$14,100	1.2%	76	\$470M	\$45.7M	212,000	124,800	19,900	1.31E-03
1	4,000	2.0	20	18.2%	\$9,800	1.7%	160	\$190M	\$18.5M	84,000	53,100	7,800	1.13E-03
2	4,000	3.0		15.0%	\$15,200	0.8%	76	\$300M	\$34.0M	119,000	73,200	11,200	1.89E-03
3	4,000	4.0		11.0%	\$16,700	0.6%	59	\$300M	\$38.4M	141,000	86,600	13,200	2.30E-03
4	4,000	5.0		6.7%	\$17,900	0.3%	40	\$300M	\$43.4M	166,000	102,300	15,500	2.72E-03
5	4,000	2.0	50	17.3%	\$7,400	2.1%	90	\$330M	\$32.5M	148,000	91,600	13,900	7.95E-04
6	4,000	3.0		14.3%	\$12,400	1.1%	49	\$560M	\$62.8M	210,000	126,400	19,700	1.32E-03
7	4,000	4.0		14.9%	\$14,700	0.7%	31	\$670M	\$89.6M	246,000	148,600	23,100	1.60E-03
8	4,000	5.0		12.1%	\$15,700	0.6%	28	\$630M	\$94.2M	286,000	174,300	26,800	1.88E-03
9	6,100	2.0	20	10.2%	\$16,700	0.7%	95	\$210M	\$20.4M	175,000	102,300	16,400	2.05E-03
10	5,700	3.0		DNC	\$7,500	4.1%	332	\$1.0B	\$49.2M	374,000	211,700	35,100	5.25E-03
11	5,400	4.0		DNC	\$7,500	4.1%	317	\$1.4B	\$76.6M	447,000	255,100	41,900	6.59E-03
12	5,000	5.0		DNC	\$7,500	4.1%	317	\$1.5B	\$89.7M	416,000	243,400	39,000	6.40E-03
13	6,100	2.0	50	12.7%	\$14,100	1.1%	60	\$550M	\$51.1M	307,000	177,700	28,800	1.45E-03
14	5,700	3.0		DNC	\$7,500	3.5%	144	\$1.8B	\$86.1M	655,000	368,500	61,400	3.68E-03
15	5,400	4.0		DNC	\$7,500	3.5%	130	\$2.4B	\$133.2M	777,000	441,300	72,800	4.58E-03
16	5,000	5.0		DNC	\$7,500	3.7%	139	\$2.5B	\$154.6M	718,000	417,300	67,300	4.41E-03

LH2 Matrix – Best Short-Range



ID: LH2.M2.28.P30.R4000.20220810



Mach 2.28
Cruise Speed



4,000 nmi
Max Range



30
Passenger Count



LH2
Fuel Type

COST METRICS (FY21 USD)

DDT&E

\$3.7B
Airframe

\$3.0B
Engine

TFU

\$90M
Airframe

\$9.4M
Engine

ENVIRONMENTAL METRICS

90 EPNdB

Lateral Takeoff Noise

0 kg/km/pax

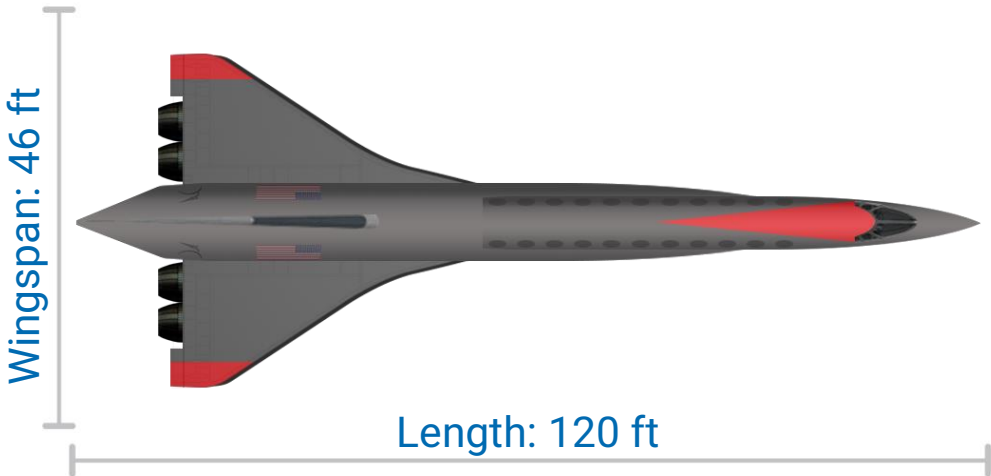
Emissions (CO2e)

103 PNLdB

Sonic Boom

0.07 kg/km/pax

Fuel Consumption Rate



116,000 lbm MTOW	72,200 lbm MEW	4 x 10,900 lbf Engine Thrust SLS
3.9 hours Gate-to-Gate Time at Max Range	61,800 ft Cruise Altitude	8,800 ft Bal. Field Length SL

AIRCRAFT NOTES

- Supersonic cruise condition L/D = 6.2
- Supersonic cruise condition Isp = 6276 s
- Vehicle propellant mass fraction (PMF) = 0.47
- Takeoff T/W = 0.375

LH2 Matrix – Best Short-Range



ID: LH2.M2.28.P30.R4000.20220810

Key Inputs

Mach 2.28
Cruise Speed

4,000 nmi
Range

30
Passenger Count

LH2
Fuel Type

OPERATOR METRICS

\$10,300-\$11,600
Ticket Price

0.6M
Pax/Year

21
Routes Captured

Cost Breakdown
88% Fuel Cost
5% Maint. Cost
7% Other DoC

MANUFACTURER METRICS

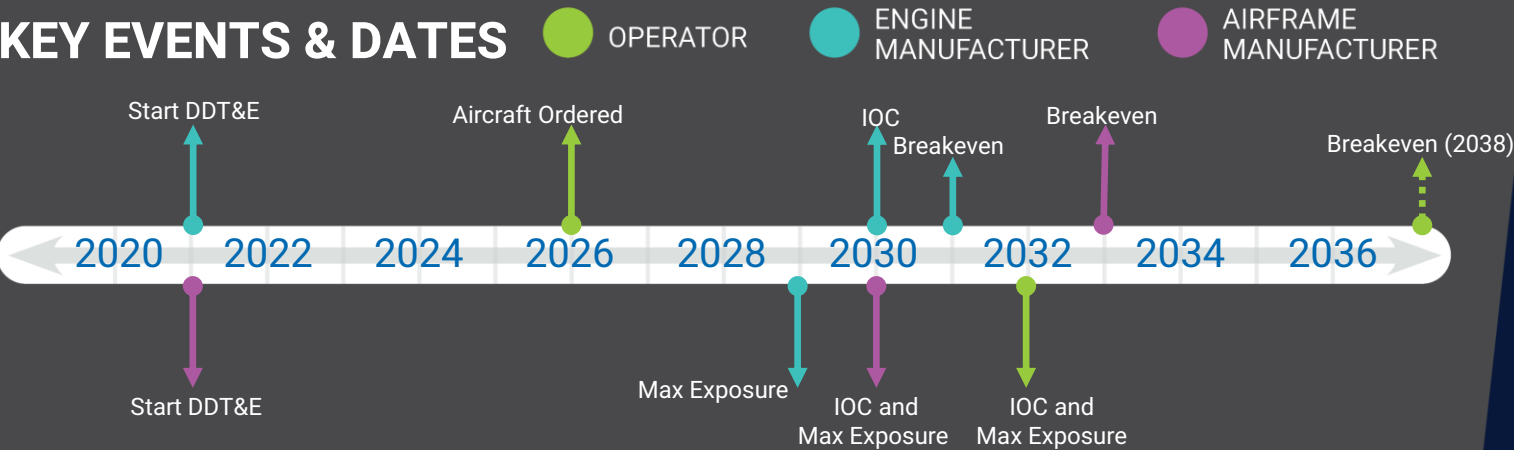
\$274M
Aircraft Price

\$161M
Airframe Price

\$28M x4
Engine Price

112
Aircraft Sold

KEY EVENTS & DATES



BUSINESS CASE ANALYSIS

This aircraft is capturing 21 of 37 addressable routes that are within its design range which are exclusively Atlantic Ocean routes. Similar to LNG, LH2 suffers from being a cryogenic and lower density fuel, but with higher fuel costs, demand capture is reduced, and 25% IRR is not achieved.

Business Results

OPERATOR

19%
IRR

\$637M
NPV

\$3.3B
Max Exposure

ENGINE MANUFACTURER

19%
IRR

\$564M
NPV

\$2.8B
Max Exposure

AIRFRAME MANUFACTURER

19%
IRR

\$861M
NPV

\$4.3B
Max Exposure

LH2 Matrix – Best Long-Range



ID: LH2.M2.00.P38.R5700.20220810



Mach 2
Cruise Speed



5,700 nmi
Max Range



38
Passenger Count



LH2
Fuel Type



COST METRICS (FY21 USD)

DDT&E

\$5.3B
Airframe

\$3.6B
Engine

TFU

\$140M
Airframe

\$16M
Engine

ENVIRONMENTAL METRICS

92 EPNdB

Lateral Takeoff Noise

0 kg/km/pax

Emissions (CO2e)

106 PNLdB

Sonic Boom

0.08 kg/km/pax

Fuel Consumption Rate

212,000 lbm MTOW	124,800 lbm MEW	4 x 19,900 lbf Engine Thrust SLS
5.8 hours Gate-to-Gate Time at Max Range	56,300 ft Cruise Altitude	8,300 ft Bal. Field Length SL

AIRCRAFT NOTES

- Supersonic cruise condition L/D = 6.7
- Supersonic cruise condition Isp = 7200 s
- Vehicle propellant mass fraction (PMF) = 0.47
- Takeoff T/W = 0.375

LH2 Matrix – Best Long-Range



ID: LH2.M2.00.P38.R5700.20220810

Key Inputs



Mach 2
Cruise Speed



5,700 nmi
Range



38
Passenger Count



LH2
Fuel Type

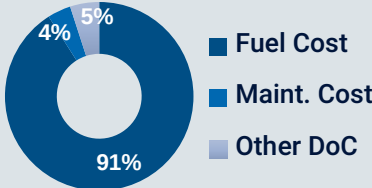


OPERATOR METRICS

\$14,100-\$18,000 **0.5M** **21**

Ticket Price

Pax/Year Routes Captured



MANUFACTURER METRICS

\$468M

Aircraft Price

\$285M

Airframe Price

\$46M x4

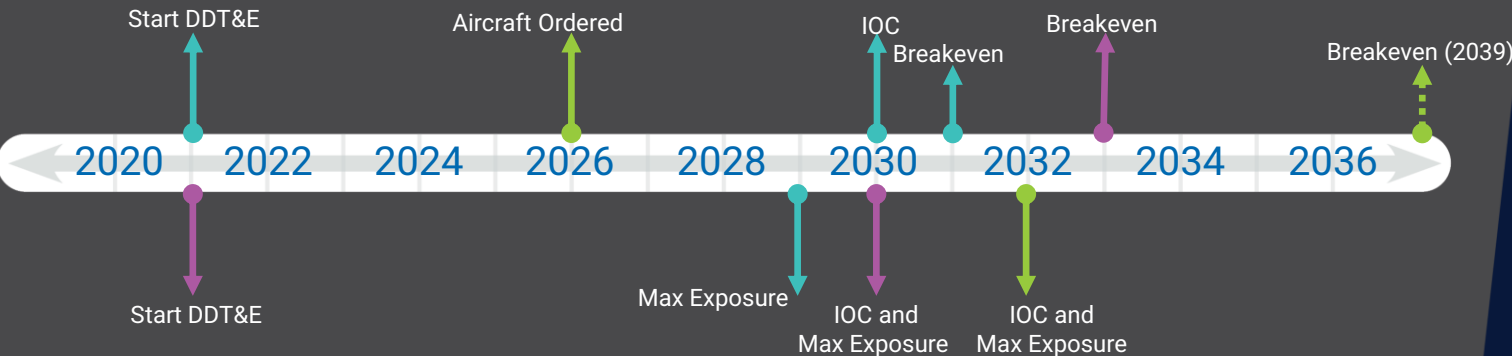
Engine Price

76

Aircraft Sold

KEY EVENTS & DATES

● OPERATOR ● ENGINE MANUFACTURER ● AIRFRAME MANUFACTURER



BUSINESS CASE ANALYSIS

This aircraft is capturing 21 of 78 addressable routes that are within its design range which are exclusively Atlantic Ocean routes. Similar to LNG, LH2 suffers from being a cryogenic and lower density fuel, but with higher fuel costs, demand capture is reduced, and 25% IRR is not achieved.

Business Results

OPERATOR

17% **\$395M** **\$4.0B**
IRR NPV Max Exposure

ENGINE MANUFACTURER

17% **\$350M** **\$3.5B**
IRR NPV Max Exposure

AIRFRAME MANUFACTURER

17% **\$582M** **\$6.0B**
IRR NPV Max Exposure

Key Takeaways

- ▶ **SAF had almost identical technical results to Jet-A but higher fuel prices early on made the economic results relatively worse when compared to Jet-A results**
 - SAF offers a plug-and-play solution to help reduce carbon emissions but is currently limited by fuel price and availability
- ▶ **LNG was able to take advantage of a low fuel price to produce economically viable business cases similar to, if not better than, Jet-A cases in most cases**
 - However, LNG tended to have higher aircraft prices than Jet-A ones as the aircraft faster and/or increased its range
 - The lower density and cryogenic fuel requirements for LNG led to heavier aircraft that begin to erase the fuel price advantage
 - This also results in greater upfront costs for the manufacturers and operators that may make the business case more daunting
- ▶ **LH2 did not have a successful case in its trade matrix due to the very low density of fuel and therefore the high quantity of fuel required per flight**
 - The performance benefits aren't enough to overcome the technical and economic challenges of LH2
- ▶ **Based on these results, and accounting for current infrastructure and environmental requirements, SpaceWorks recommends SAF to be the fuel to replace Jet-A**
 - The cryogenic fuels have potential but the required developments for these fuels make them more appealing as viable options once the technical challenges are more under control



Overland Routes Sensitivity Study

Objective

- ▶ **Re-evaluate the economic performance of single aircraft and mixed fleet business cases for the Jet-A Trade Matrix with Overland Routes considered**
 - U.S. Domestic Routes
 - Additional International Routes with overland segments
- ▶ **The main objective was to determine if the addition of overland routes generated more favorable business cases assuming the sonic boom restrictions and other regulatory issues are overcome**
- ▶ **For the trade matrices, short-range aircraft were set to 4000 nmi design range, and long-range aircraft design range varied with Mach number**
 - Long-range aircraft become infeasible at higher Mach regimes

Case	Range	PAX	Cruise Mach	Fuel Type
Baseline-A	Short	Best	Best	Jet-A
Baseline-B	Long	Best	Best	Jet-A
1	Short	20	2	Jet-A
2	Short	20	3	Jet-A
3	Short	20	4	Jet-A
4	Short	20	5	Jet-A
5	Short	50	2	Jet-A
6	Short	50	3	Jet-A
7	Short	50	4	Jet-A
8	Short	50	5	Jet-A
9	Long	20	2	Jet-A
10	Long	20	3	Jet-A
11	Long	20	4	Jet-A
12	Long	20	5	Jet-A
13	Long	50	2	Jet-A
14	Long	50	3	Jet-A
15	Long	50	4	Jet-A
16	Long	50	5	Jet-A

▶ **Passenger demand data was gathered from the Bureau of Transportation Statistics: T-100 Domestic Market & T-100 International Market data files for 2019**

- Data was filtered down based on the following requirements:
 - Domestic routes must fly between major U.S. airports (see Appendix for list of Airports)
 - International routes must fly to or from the “large” subset of major U.S. airports
 - Routes must have more than 100,000 annual passengers

▶ **The ROSETTA Model integrated these routes by breaking out Domestic and International Overland routes in 3 categories based on passenger demand**

- Routes with 100,000 – 499,999 annual passengers were considered “Small”
- Routes with 500,000 – 999,999 annual passengers were considered “Medium”
- Routes with 1,000,000+ annual passengers were considered “Large”

▶ **For fleet calculations, the average route demand & weighted average route distance were used as a representative route for each category**

- This was done to fairly eliminate routes based on market capture
- Key calculations were scaled back up using the number of routes captured in each category

Major Overland Route Assumptions

- ▶ **The distribution of Economy passengers versus Premium passengers was adjusted for overland routes to be more conservative and reflect the diminishing returns of high-speed flight at shorter ranges**
 - Original routes distribution: 84.7% Economy, 15.3% Premium
 - Domestic routes distribution: 95% Economy, 5% Premium
 - Based on seat configurations for commercial aircraft (~5-10% are Premium)
 - International Overland routes distribution: 88% Economy, 12% Premium
 - Slightly adjusted from Original to reflect shorter North American routes (e.g., US to Canada or US to Mexico)
- ▶ **Mach number sets the minimum distance for viable routes**
 - Minimum distance based on Mach is determine by calculating distance needed to achieve 30 minutes of cruise time
 - Curve fit used to determine minimum distances at intermediate Mach numbers (e.g., Mach 2.5 or Mach 3.24)

Mach	Minimum Distance	Addressable Domestic Market (Routes)	Addressable International Overland Market (Routes)
2	1,000 nmi	191,000,000 (381)	104,000,000 (384)
3	1,600 nmi	78,400,000 (161)	69,600,000 (268)
4	2,300 nmi	5,970,000 (20)	54,400,000 (209)
5	3,000 nmi	1,710,000 (8)	48,600,000 (184)

Economic Comparison

BASELINE										OVERLAND ROUTES					
Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price
1	4,000	2.0	20	25.1%	\$5,000	1.5M	289	\$170M	\$13.5M	27.2%	\$11,000	2.9M	966	\$140M	\$11.3M
2	4,000	3.0		25.5%	\$7,000	1.1M	207	\$260M	\$23.4M	28.2%	\$10,200	1.6M	446	\$210M	\$19.2M
3	4,000	4.0		25.0%	\$10,000	0.77M	152	\$380M	\$37.1M	25.6%	\$10,100	0.95M	206	\$350M	\$33.3M
4	4,000	5.0		25.2%	\$12,700	0.60M	123	\$450M	\$50.0M	25.0%	\$10,700	0.90M	186	\$380M	\$39.4M
5	4,000	2.0	50	25.0%	\$4,300	1.6M	143	\$350M	\$27.8M	25.2%	\$5,500	9.4M	1055	\$200M	\$14.3M
6	4,000	3.0		25.1%	\$5,700	1.4M	111	\$470M	\$43.1M	25.5%	\$5,000	4.8M	485	\$250M	\$22.3M
7	4,000	4.0		24.9%	\$11,500	0.58M	53	\$990M	\$97.6M	25.0%	\$8,400	0.98M	112	\$550M	\$55.6M
8	4,000	5.0		23.7%	\$11,500	0.64M	61	\$980M	\$105.2M	24.8%	\$11,000	0.80M	92	\$740M	\$78.9M
9	6,100	2.0	20	25.0%	\$8,200	1.4M	324	\$210M	\$17.0M	25.3%	\$9,200	4.2M	1159	\$150M	\$13.4M
10	5,700	3.0		22.1%	\$13,100	0.81M	188	\$370M	\$34.9M	24.1%	\$14,000	1.2M	377	\$300M	\$28.8M
11	5,400	4.0		19.0%	\$15,500	0.45M	101	\$520M	\$57.0M	19.4%	\$14,700	0.75M	207	\$400M	\$45.2M
12	5,000	5.0		18.4%	\$15,000	0.54M	120	\$480M	\$58.5M	18.0%	\$15,000	0.68M	180	\$450M	\$56.6M
13	6,100	2.0	50	25.0%	\$8,300	1.1M	131	\$530M	\$41.9M	25.5%	\$7,700	3.9M	616	\$270M	\$23.7M
14	5,700	3.0		21.3%	\$11,600	0.78M	81	\$850M	\$77.5M	22.3%	\$12,900	0.73M	100	\$750M	\$68.7M
15	5,400	4.0		18.6%	\$11,600	0.80M	81	\$870M	\$90.8M	18.9%	\$13,100	0.64M	79	\$900M	\$93.1M
16	5,000	5.0		18.4%	\$12,200	0.75M	74	\$950M	\$108.5M	18.4%	\$12,800	0.86M	131	\$700M	\$91.5M

Overland Matrix – Best Short-Range



ID: JTA.M2.07.P88.R4000.OLR.20220820



Mach 2.07
Cruise Speed



4,000 nmi
Max Range



88
Passenger Count



JetA
Fuel Type

COST METRICS (FY21 USD)

DDT&E

\$5.0B
Airframe

\$2.5B
Engine

TFU

\$138M
Airframe

\$18M
Engine

ENVIRONMENTAL METRICS

93 EPNdB

Lateral Takeoff Noise

0.3 kg/km/pax

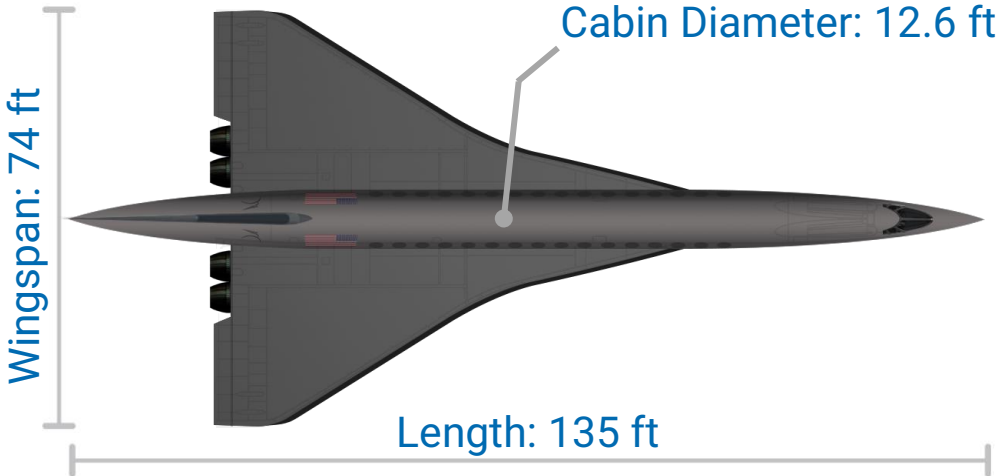
Emissions (CO₂e)

106 PNLdB

Sonic Boom

0.09 kg/km/pax

Fuel Consumption Rate



269,000 lbm MTOW	108,100 lbm MEW	4 x 25,200 lbf Engine Thrust SLS
4.2 hours Gate-to-Gate Time at Max Range	57,700 ft Cruise Altitude	6,600 ft Bal. Field Length SL

AIRCRAFT NOTES

- Supersonic cruise condition L/D = 7.8
- Supersonic cruise condition Isp = 2897 s
- Vehicle propellant mass fraction (PMF) = 0.47
- Takeoff T/W = 0.375

Overland Matrix – Best Short-Range



ID: JTA.M2.07.P88.R4000.OLR.20220820

Key Inputs

Mach 2.07
Cruise Speed

4,000 nmi
Range

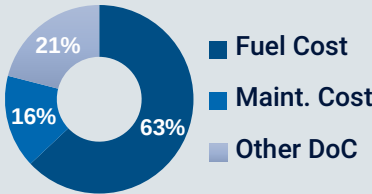
88
Passenger Count

JetA
Fuel Type



OPERATOR METRICS

\$3,200-\$3,500 **17M** **25**
Ticket Price Pax/Year Routes Captured

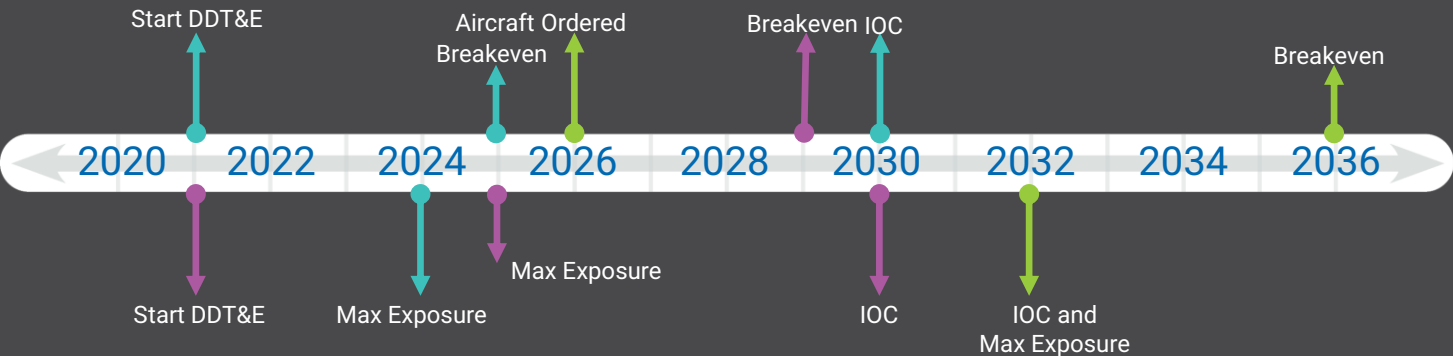


MANUFACTURER METRICS

\$213M **\$139M** **\$18M x4** **1048**
Aircraft Price Airframe Price Engine Price Aircraft Sold

KEY EVENTS & DATES

● OPERATOR ● ENGINE MANUFACTURER ● AIRFRAME MANUFACTURER



BUSINESS CASE ANALYSIS

This aircraft is capturing 27 of 45 addressable routes (of the original 90) that are within its design range which are exclusively Atlantic Ocean routes. Since the aircraft is more passenger efficient, ticket prices can be lower to capture a significant amount of demand to offset acquisitions.

Business Results

OPERATOR

25% **\$15B** **\$20B**
IRR NPV Max Exposure

ENGINE MANUFACTURER

59% **\$3.1B** **\$834M**
IRR NPV Max Exposure

AIRFRAME MANUFACTURER

29% **\$3.0B** **\$3.7B**
IRR NPV Max Exposure

Overland Matrix – Best Long-Range



ID: JTA.M2.1.P39.R5700.OLR.20220820



Mach 2.1
Cruise Speed



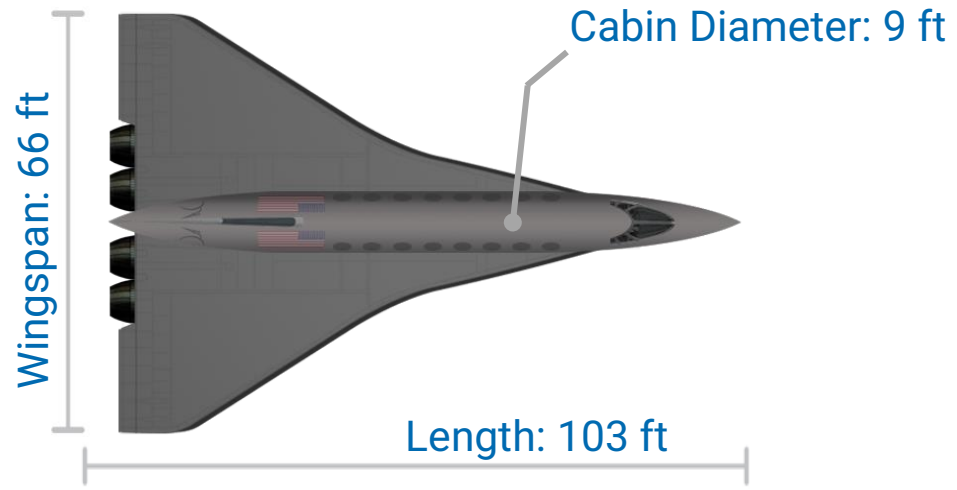
5,700 nmi
Max Range



39
Passenger Count



JetA
Fuel Type



COST METRICS (FY21 USD)

DDT&E

\$4.3B
Airframe

\$2.4B
Engine

TFU

\$115M
Airframe

\$17M
Engine

ENVIRONMENTAL METRICS

93 EPNdB
Lateral Takeoff Noise

0.52 kg/km/pax
Emissions (CO2e)

105 PNLdB
Sonic Boom

0.16 kg/km/pax
Fuel Consumption Rate

240,000 lbm MTOW	81,600 lbm MEW	4 x 22,500 lbf Engine Thrust SLS
5.6 hours Gate-to-Gate Time at Max Range	58,100 ft Cruise Altitude	6,700 ft Bal. Field Length SL

AIRCRAFT NOTES

- Supersonic cruise condition L/D = 7.8
- Supersonic cruise condition Isp = 2870 s
- Vehicle propellant mass fraction (PMF) = 0.47
- Takeoff T/W = 0.375

Overland Matrix – Best Long-Range



ID: JTA.M2.1.P39.R5700.OLR.20220820

Key Inputs

Mach 2.1
Cruise Speed

5,700 nmi
Range

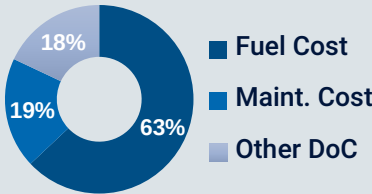
39
Passenger Count

JetA
Fuel Type



OPERATOR METRICS

\$5,700-\$7,300 **9.4M** **50**
Ticket Price Pax/Year Routes Captured

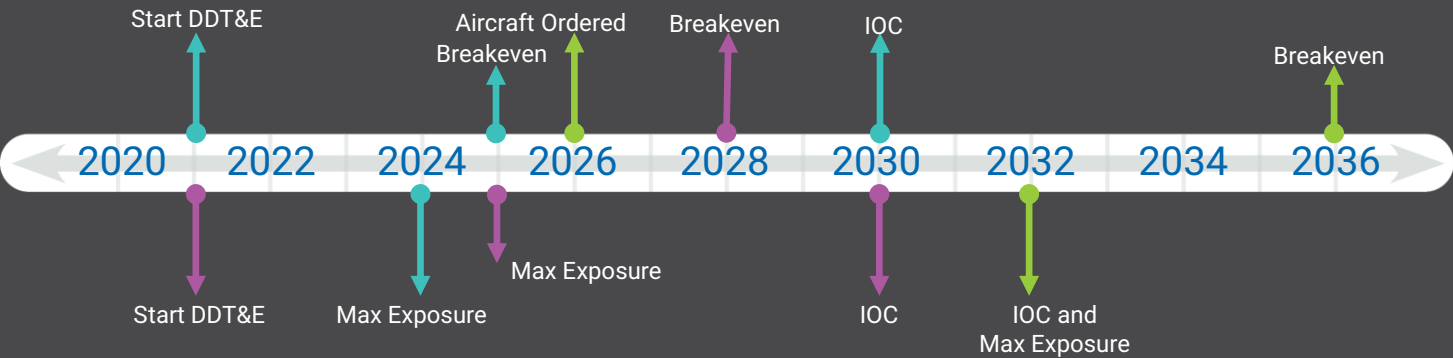


MANUFACTURER METRICS

\$182M **\$115M** **\$17M x4** **1173**
Aircraft Price Airframe Price Engine Price Aircraft Sold

KEY EVENTS & DATES

● OPERATOR ● ENGINE MANUFACTURER ● AIRFRAME MANUFACTURER



BUSINESS CASE ANALYSIS

This aircraft is capturing 50 of 78 addressable routes (of the original 90) that are within its design range which are exclusively Atlantic Ocean routes. Since the aircraft is more passenger efficient, ticket prices can be lower and higher acquisition costs are offset by less aircraft being needed.

Business Results

OPERATOR

25% **\$15B** **\$20B**
IRR NPV Max Exposure

ENGINE MANUFACTURER

65% **\$3.2B** **\$806M**
IRR NPV Max Exposure

AIRFRAME MANUFACTURER

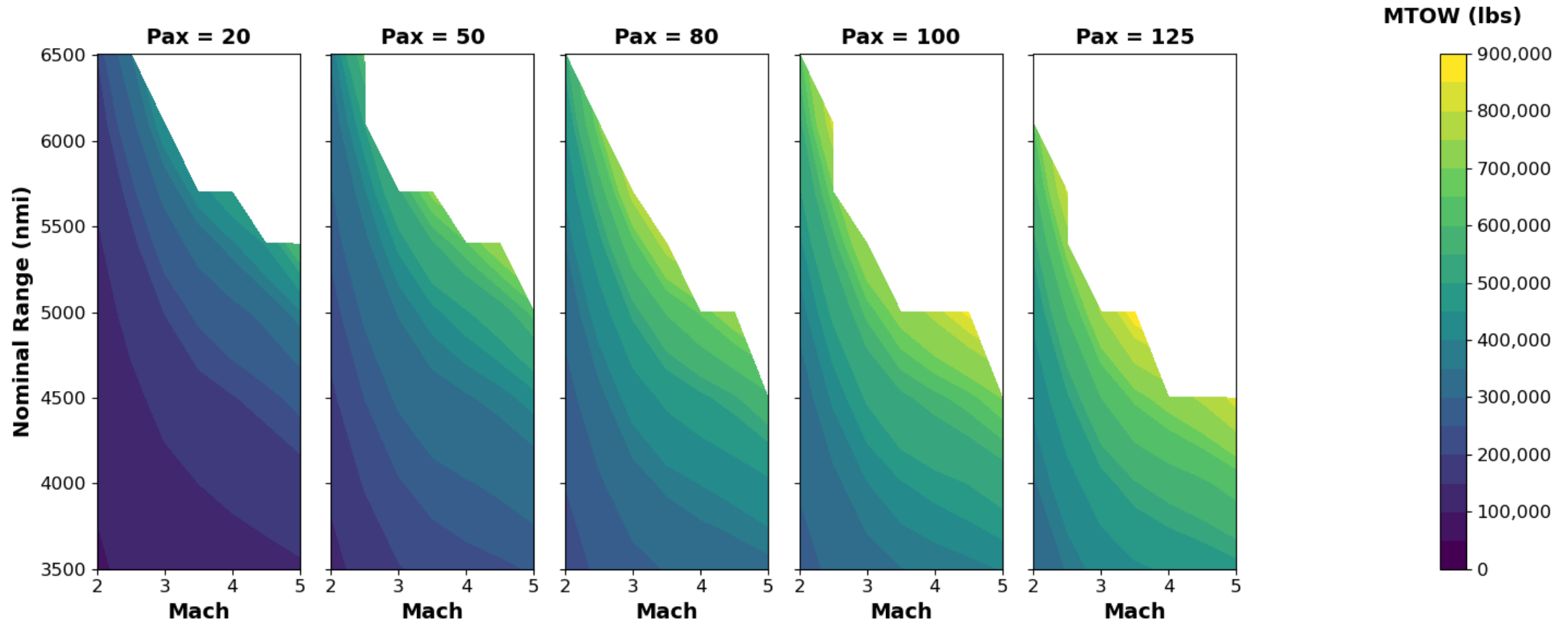
30% **\$2.7B** **\$3.5B**
IRR NPV Max Exposure



Full Trade Space Analysis

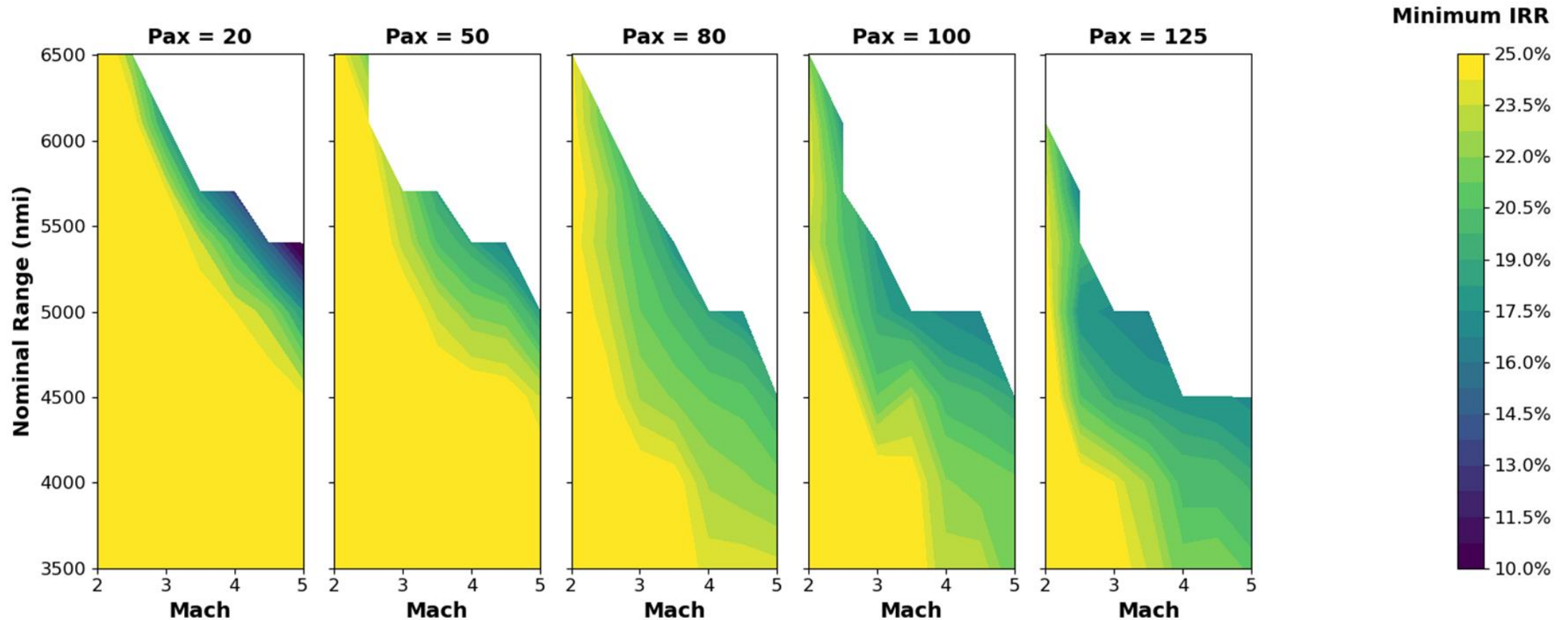
Overland Route Analysis | MTOW

- For the purposes of this analysis, aircraft with a MTOW over 1,000,000 lbs were considered oversized for most runways and therefore removed from the economic analysis



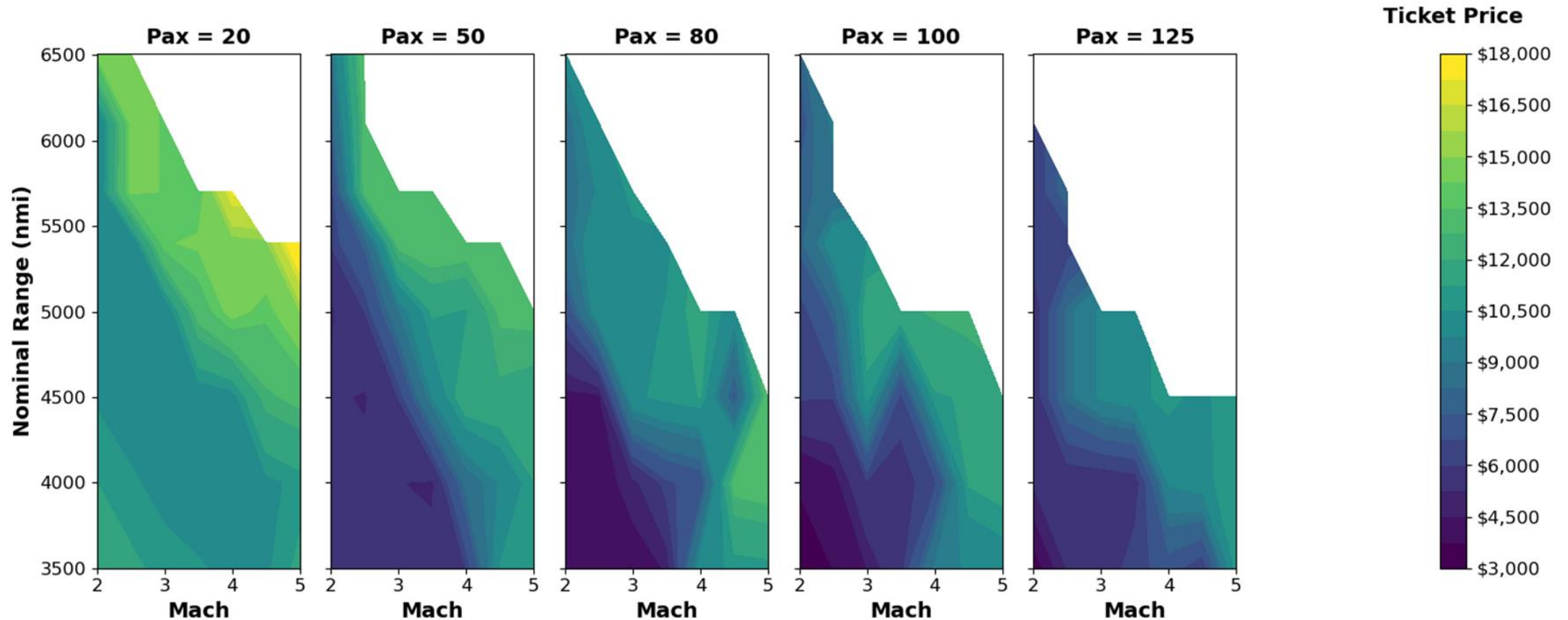
Overland Route Analysis | IRR

- ▶ The 20-50 passenger aircraft all mostly achieved 25% IRR while the larger aircraft falter at higher Mach numbers but still had successful cases at lower Mach, short-medium haul ranges
- ▶ Cases that did not close were removed from the analysis



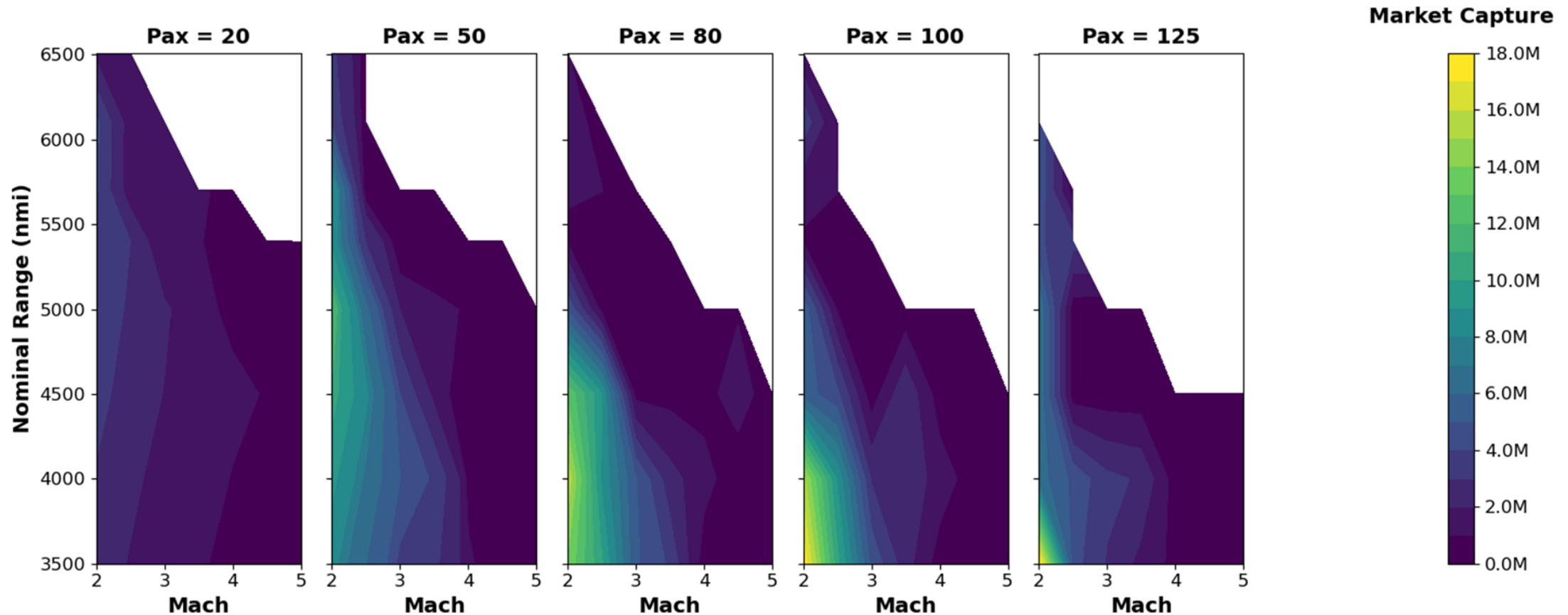
Overland Route Analysis | Ticket Price

- 20 passenger aircraft are too inefficient for the increase in demand, so higher ticket prices aim to drive down that demand
- 80 passenger aircraft at low Mach and Range is the best, largest region for ticket price



Overland Route Analysis | Market Capture

- ▶ Reflective of ticket price, the highest demand capture actual occurs with the larger aircraft that are the most passenger efficient (80-125)
- ▶ The 50 passenger cases had greater geographical capture though (longer ranges)





Alternative Fuel Inquiry

▣ LNG & LH2

Overview

- ▶ **Wanted to see if cryogenic fuels performed better economically at lower ranges (i.e., smaller aircraft) but with a sufficient addressable market**
- ▶ **Previously, LNG achieved a 25% IRR but had higher upfront costs in some cases**
- ▶ **LH2 failed to achieve a 25% IRR for any case, largely due to high fuel costs**
- ▶ **The results found in this inquiry show that LNG continues to perform well but the most notable result is that LH2 achieves 25% IRR for Mach 2 aircraft at the lower ranges**
 - This may suggest that there is a Hydrogen solution for high-speed aircraft that could address short-haul routes
- ▶ **NOTE: These cases are not one-to-one comparisons for baseline-to-overland**

LNG (Baseline)

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
Best – SR	4,000	2.41	39	25.0%	\$3,500	5.4%	204	\$310M	\$27.9M	170,000	72,700	16,000	0.38
Best – LR	5,700	2.00	39	25.1%	\$4,900	6.2%	309	\$310M	\$25.7M	258,000	98,700	24,200	0.45
1	4,000	2.0	20	25.0%	\$3,900	4.8%	374	\$160M	\$13.8M	99,000	45,200	9,300	0.40
2	4,000	3.0		25.1%	\$5,300	4.0%	295	\$240M	\$23.0M	143,000	59,300	13,400	0.67
3	4,000	4.0		25.1%	\$7,200	2.9%	214	\$330M	\$36.2M	167,000	68,500	15,600	0.80
4	4,000	5.0		25.4%	\$12,600	1.5%	126	\$530M	\$66.2M	187,000	77,700	17,600	0.90
5	4,000	2.0	50	25.0%	\$3,700	4.8%	165	\$360M	\$31.5M	175,000	77,700	16,400	0.29
6	4,000	3.0		25.0%	\$5,200	3.8%	126	\$500M	\$50.7M	251,000	101,900	23,500	0.47
7	4,000	4.0		24.6%	\$6,400	3.2%	106	\$650M	\$71.7M	290,000	117,000	27,200	0.55
8	4,000	5.0		23.5%	\$10,400	1.8%	69	\$990M	\$117.0M	323,000	131,800	30,300	0.62
9	6,100	2.0	20	25.0%	\$7,300	4.1%	381	\$240M	\$20.0M	207,000	77,400	19,400	0.70
10	5,700	3.0		21.9%	\$15,200	1.3%	126	\$560M	\$57.6M	405,000	137,900	38,000	1.59
11	5,400	4.0		20.2%	\$14,700	1.4%	128	\$600M	\$69.1M	457,000	157,800	42,900	1.89
12	5,000	5.0		20.8%	\$15,000	1.4%	119	\$640M	\$80.7M	406,000	147,300	38,100	1.76
13	6,100	2.0	50	25.4%	\$8,800	2.7%	128	\$630M	\$59.1M	364,000	133,900	34,100	0.49
14	5,700	3.0		19.7%	\$11,000	2.2%	94	\$940M	\$91.5M	709,000	239,300	66,500	1.11
15	5,400	4.0		17.9%	\$11,300	2.1%	88	\$1.0B	\$116.5M	795,000	272,100	74,500	1.31
16	5,000	5.0		18.8%	\$11,500	2.1%	81	\$1.1B	\$137.0M	700,000	251,600	65,700	1.21

LNG (Overland Routes)

Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
3,000	2.0	20	28.4%	\$12,000	0.8%	843	\$130M	\$12.3M	76,000	38,200	7,100	0.35
3,000	3.0		26.1%	\$11,300	0.7%	323	\$220M	\$21.1M	97,000	45,500	9,100	0.52
3,000	4.0		21.6%	\$6,600	1.8%	297	\$200M	\$20.1M	107,000	50,100	10,100	0.58
3,000	5.0		20.8%	\$5,900	1.2%	80	\$420M	\$51.7M	114,000	54,400	10,700	0.61
3,000	2.0	50	25.1%	\$6,100	2.5%	838	\$250M	\$14.3M	134,000	65,600	12,600	0.25
3,000	3.0		27.0%	\$5,700	2.2%	364	\$280M	\$27.5M	170,000	77,800	16,000	0.36
3,000	4.0		19.9%	\$5,300	1.4%	61	\$590M	\$68.2M	187,000	85,200	17,500	0.41
3,000	5.0		17.9%	\$6,600	1.0%	33	\$860M	\$92.2M	197,000	91,600	18,500	0.42
3,500	2.0	20	26.1%	\$11,600	0.9%	912	\$140M	\$8.4M	86,000	41,400	8,100	0.37
3,500	3.0		27.7%	\$10,800	0.9%	393	\$230M	\$20.7M	116,000	51,300	10,900	0.58
3,500	4.0		25.3%	\$10,300	1.2%	148	\$440M	\$44.0M	132,000	57,700	12,300	0.67
3,500	5.0		25.0%	\$10,700	1.4%	129	\$490M	\$55.9M	143,000	63,700	13,400	0.72
3,500	2.0	50	25.8%	\$5,800	2.8%	1047	\$160M	\$15.9M	152,000	71,100	14,300	0.26
3,500	3.0		27.3%	\$5,400	2.9%	428	\$290M	\$24.9M	204,000	88,000	19,200	0.41
3,500	4.0		25.6%	\$5,900	2.5%	126	\$530M	\$57.5M	229,000	98,300	21,500	0.47
3,500	5.0		24.2%	\$6,400	2.6%	100	\$660M	\$77.8M	248,000	107,700	23,200	0.50

LH2 (Baseline)

Matrix	Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
Best – SR	4,000	2.28	30	19.0%	\$10,300	1.6%	112	\$270M	\$28.1M	116,000	72,200	10,900	1.11E-03
Best – LR	5,700	2.00	38	17.2%	\$14,100	1.2%	76	\$470M	\$45.7M	212,000	124,800	19,900	1.31E-03
1	4,000	2.0	20	18.2%	\$9,800	1.7%	160	\$190M	\$18.5M	84,000	53,100	7,800	1.13E-03
2	4,000	3.0		15.0%	\$15,200	0.8%	76	\$300M	\$34.0M	119,000	73,200	11,200	1.89E-03
3	4,000	4.0		11.0%	\$16,700	0.6%	59	\$300M	\$38.4M	141,000	86,600	13,200	2.30E-03
4	4,000	5.0		6.7%	\$17,900	0.3%	40	\$300M	\$43.4M	166,000	102,300	15,500	2.72E-03
5	4,000	2.0	50	17.3%	\$7,400	2.1%	90	\$330M	\$32.5M	148,000	91,600	13,900	7.95E-04
6	4,000	3.0		14.3%	\$12,400	1.1%	49	\$560M	\$62.8M	210,000	126,400	19,700	1.32E-03
7	4,000	4.0		14.9%	\$14,700	0.7%	31	\$670M	\$89.6M	246,000	148,600	23,100	1.60E-03
8	4,000	5.0		12.1%	\$15,700	0.6%	28	\$630M	\$94.2M	286,000	174,300	26,800	1.88E-03
9	6,100	2.0	20	10.2%	\$16,700	0.7%	95	\$210M	\$20.4M	175,000	102,300	16,400	2.05E-03
10	5,700	3.0		DNC	\$7,500	4.1%	332	\$1.0B	\$49.2M	374,000	211,700	35,100	5.25E-03
11	5,400	4.0		DNC	\$7,500	4.1%	317	\$1.4B	\$76.6M	447,000	255,100	41,900	6.59E-03
12	5,000	5.0		DNC	\$7,500	4.1%	317	\$1.5B	\$89.7M	416,000	243,400	39,000	6.40E-03
13	6,100	2.0	50	12.7%	\$14,100	1.1%	60	\$550M	\$51.1M	307,000	177,700	28,800	1.45E-03
14	5,700	3.0		DNC	\$7,500	3.5%	144	\$1.8B	\$86.1M	655,000	368,500	61,400	3.68E-03
15	5,400	4.0		DNC	\$7,500	3.5%	130	\$2.4B	\$133.2M	777,000	441,300	72,800	4.58E-03
16	5,000	5.0		DNC	\$7,500	3.7%	139	\$2.5B	\$154.6M	718,000	417,300	67,300	4.41E-03

LH2 (Overland Routes)

Range (nmi)	Mach	Pax	Min. IRR	Ticket Price	Market Capture	Aircraft Sold	Aircraft Price	Engine Price	MTOW (lbm)	MEW (lbm)	Engine Thrust (lbf)	CO2e (kg/km/pax)
3,000	2.0	20	25.5%	\$12,000	0.8%	849	\$110	\$9.3	65,000	43,100	6,100	9.65E-04
3,000	3.0		19.1%	\$13,900	0.3%	176	\$210	\$21.5	82,000	52,900	7,700	1.43E-03
3,000	4.0		12.1%	\$13,600	0.4%	65	\$240	\$30.7	91,000	59,000	8,600	1.63E-03
3,000	5.0		11.4%	\$17,300	0.2%	22	\$350	\$48.8	100,000	65,100	9,300	1.76E-03
3,000	2.0	50	24.4%	\$11,800	0.5%	403	\$200	\$16.9	116,000	74,200	10,800	6.84E-04
3,000	3.0		17.6%	\$12,400	0.4%	158	\$280	\$29.2	144,000	90,900	13,500	1.00E-03
3,000	4.0		12.8%	\$13,200	0.3%	25	\$490	\$62.2	159,000	100,700	14,900	1.13E-03
3,000	5.0		13.0%	\$11,200	0.5%	23	\$560	\$84.3	172,000	110,200	16,100	1.22E-03
3,500	2.0	20	26.2%	\$14,300	0.4%	465	\$170	\$14.1	73,000	47,600	6,900	1.03E-03
3,500	3.0		18.4%	\$13,900	0.5%	234	\$200	\$19.7	98,000	61,400	9,200	1.61E-03
3,500	4.0		12.7%	\$16,100	0.4%	85	\$230	\$29.2	112,000	70,200	10,500	1.89E-03
3,500	5.0		8.8%	\$17,900	0.2%	37	\$330	\$47.1	125,000	79,500	11,700	2.13E-03
3,500	2.0	50	25.0%	\$9,800	0.8%	441	\$210	\$17.2	130,000	82,000	12,200	7.31E-04
3,500	3.0		18.5%	\$12,700	0.6%	188	\$290	\$29.7	172,000	105,800	16,100	1.13E-03
3,500	4.0		14.1%	\$14,500	0.5%	31	\$740	\$75.9	194,000	120,000	18,200	1.32E-03
3,500	5.0		15.2%	\$15,000	0.6%	28	\$710	\$104.9	216,000	135,000	20,300	1.47E-03



Conclusions & Takeaways

Conclusions & Takeaways

- ▶ **With a greater addressable market, the business cases improve but also result in greater ticket prices in most cases to reduce demand, and therefore, acquisition costs**
 - This may suggest that a competitive market space is better suited for the larger market where manufacturers maintain high production levels, but operators don't have to acquire a large amount of aircraft to address the market on their own
 - This is similar to what we are seeing with Boom Overture orders from United and American Airlines

- ▶ **Looking at alternative fuel solutions, specifically LNG & LH2 at shorter ranges, indicate that the smaller aircraft have improved business cases**
 - All Mach 2 hydrogen business cases successfully closed which may indicate that high-speed hydrogen aircraft are best suited for short haul applications rather than long-range, transoceanic markets

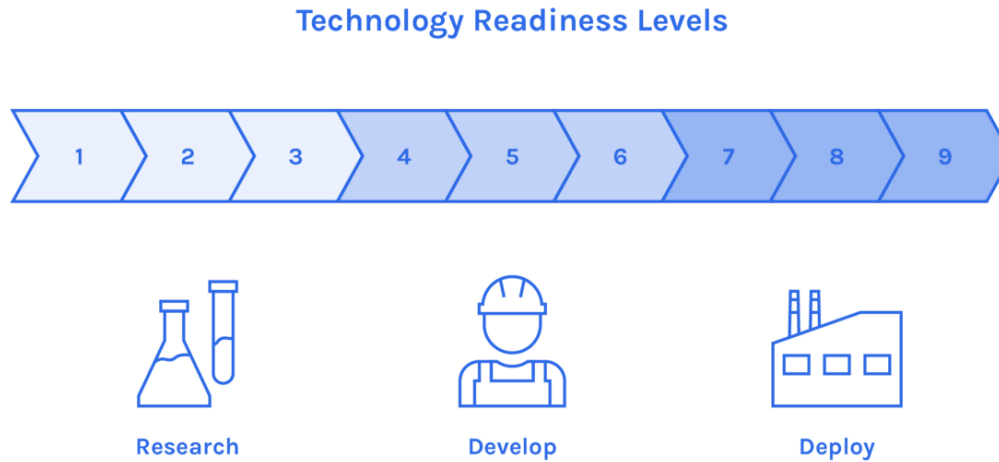
- ▶ **Ultimately, the larger addressable market provides a significant boost to business cases but it does put strain on the Operator's business cases to acquire aircraft and fully address this market on its own**
 - Preliminary mixed fleet solutions do show improvements with "international" and "domestic" fleets but still result in high acquisition costs
 - Again, a competitive business case may have a better economic performance overall
 - Mixed fleet results also still suggest that demand should drive the aircraft split rather than distance



IOC Sensitivity Study

Objective

- ▶ Evaluate the technical and economic impact of delaying the IOC of an aircraft type and allowing market growth, technology development and maturity, and economic improvements or degradations
- ▶ Based on the set of “k-factors” developed, SpaceWorks should be able to identify the focus area(s) with the greatest impact on the business case
 - This should drive recommendations to NASA



▤ SpaceWorks internally developed a sets of k-factors to forecast how technical and economic parameters may change over time

- SpaceWorks conducted an internal survey, using company SMEs, to provide their inputs for how they expect factors to change over time
- SMEs were asked to only fill out areas they had familiarity with and then their responses were weighted to calculate average values
 - A structures engineer may fill out structures and propulsion areas while omitting economics but then their responses for structures would be given more weight
- The k-factors were reviewed by NASA and approved after an iteration
- The following areas were evaluated for k-factors
 - Structures
 - Propulsion
 - Noise
 - Fuel
 - Economics

▤ K-factors were then applied accordingly based on the IOC date in the model

▶ Technical k-factors:

Structures k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Structures Mass Reduction	Mass	0%	-4.0%	-7.0%	-9.0%	-11.0%	-12.5%
TPS Mass Reduction	Mass	0%	-4.0%	-7.5%	-10.0%	-12.5%	-14.5%
L/D	L/D	0%	+1.0%	+3.0%	+5.0%	+6.0%	+7.0%

Propulsion k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Engine T/W	T/W	0%	+4.0%	+8.0%	+11.5%	+13.5%	+15.5%
Isp	Fuel Eff.	0%	+2.5%	+5.0%	+7.0%	+8.5%	+10.0%
Emissions	CO2e	0%	-2.5%	-4.0%	-7.0%	-8.0%	-9.0%

Noise k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Sideline Noise	Takeoff Noise	0%	-3.0%	-6.0%	-7.0%	-9.0%	-10.0%
Overpressure	Overpressure	0%	-9.0%	-13.5%	-15.0%	-21.5%	-22.5%

▶ Economic k-factors:

Fuel k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Jet-A Prices	Fuel Cost	0%	+9.0%	+15.5%	+27.5%	+42.5%	+53.0%
LNG Prices	Fuel Cost	0%	0.0%	+2.5%	+4.5%	+8.0%	+13.5%
SAF Prices	Fuel Cost	0%	-12.0%	-21.0%	-29.0%	-42.0%	-45.5%
LH2 Prices	Fuel Cost	0%	-5.5%	-8.0%	-16.0%	-28.0%	-62.0%

Economic k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Maintenance	Maint. Costs	0%	-4.5%	-10.5%	-18.0%	-29.0%	-38.5%
Airframe Manufacturing	TFU	0%	-6.5%	-10.5%	-14.5%	-19.5%	-26.0%
Engine Manufacturing	TFU	0%	-6.5%	-10.5%	-14.5%	-19.5%	-26.0%
Tax Benefits / Detriments	Cost	0%	-7%	-5.0%	-3.5%	-2.5%	-2.0%

Major IOC Assumptions

▶ **The Engine Manufacturer's IOC date was used as the reference IOC**

- This determined which k-factor value was used for analysis based on that reference IOC date

▶ **k-factors were applied at a single point in sizing and costing calculations for a one-time impact to that value**

- Fuel, Maintenance, and Taxes Benefits were assumed to change overtime and were therefore, phased annually to reflect macroeconomic changes that weren't restricted to an IOC date

▶ **Model years were held constant from 2022-2057 to reflect 10 years of development and 25 years of operations**

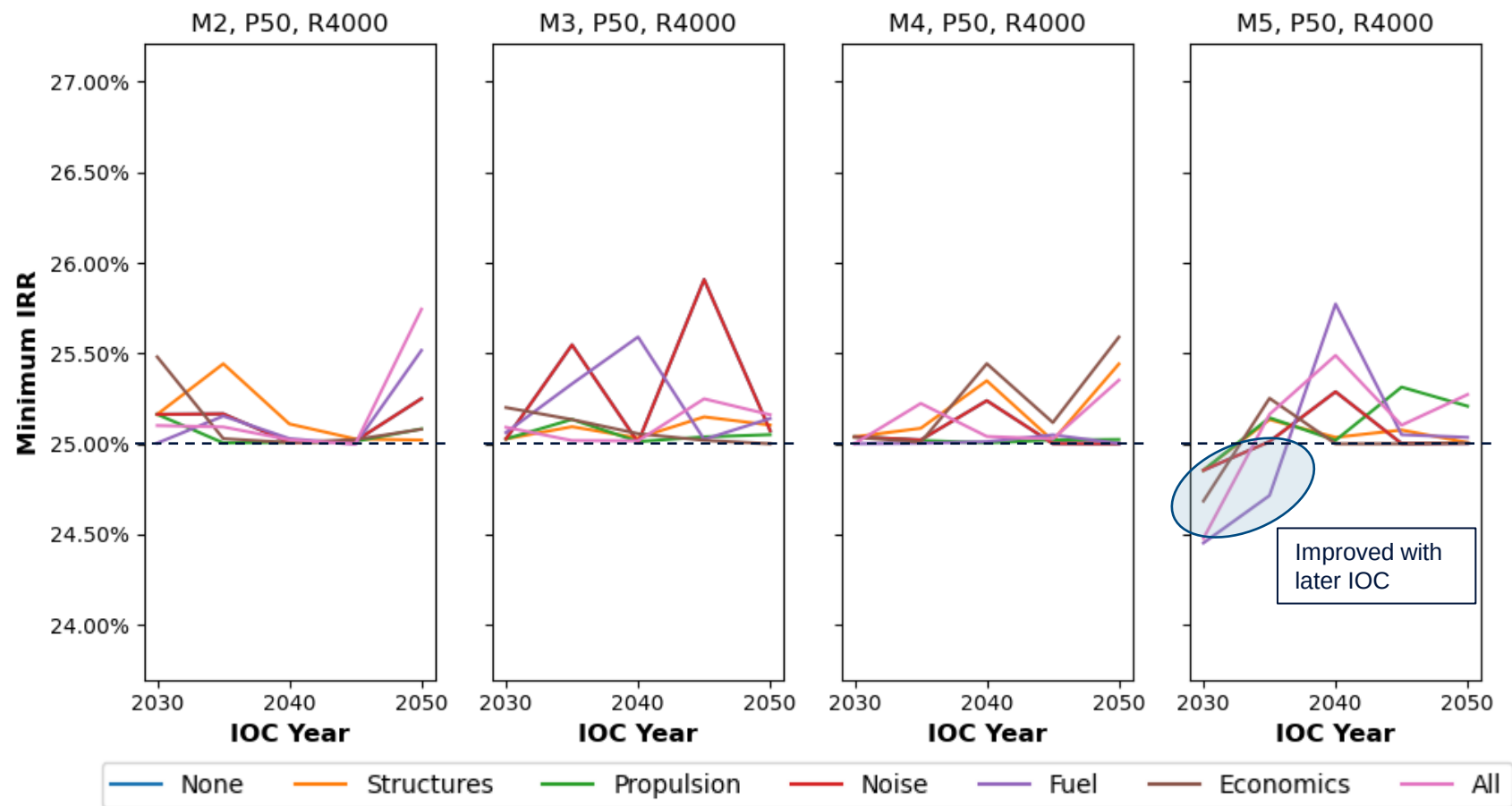
▶ **Terminal Values were used to project out years when a later IOC date prevented the full length of operations to be captured**

- Final year cash flows were based on final year EBITDA times the number of operational years remaining

IOC Sensitivity Study Results

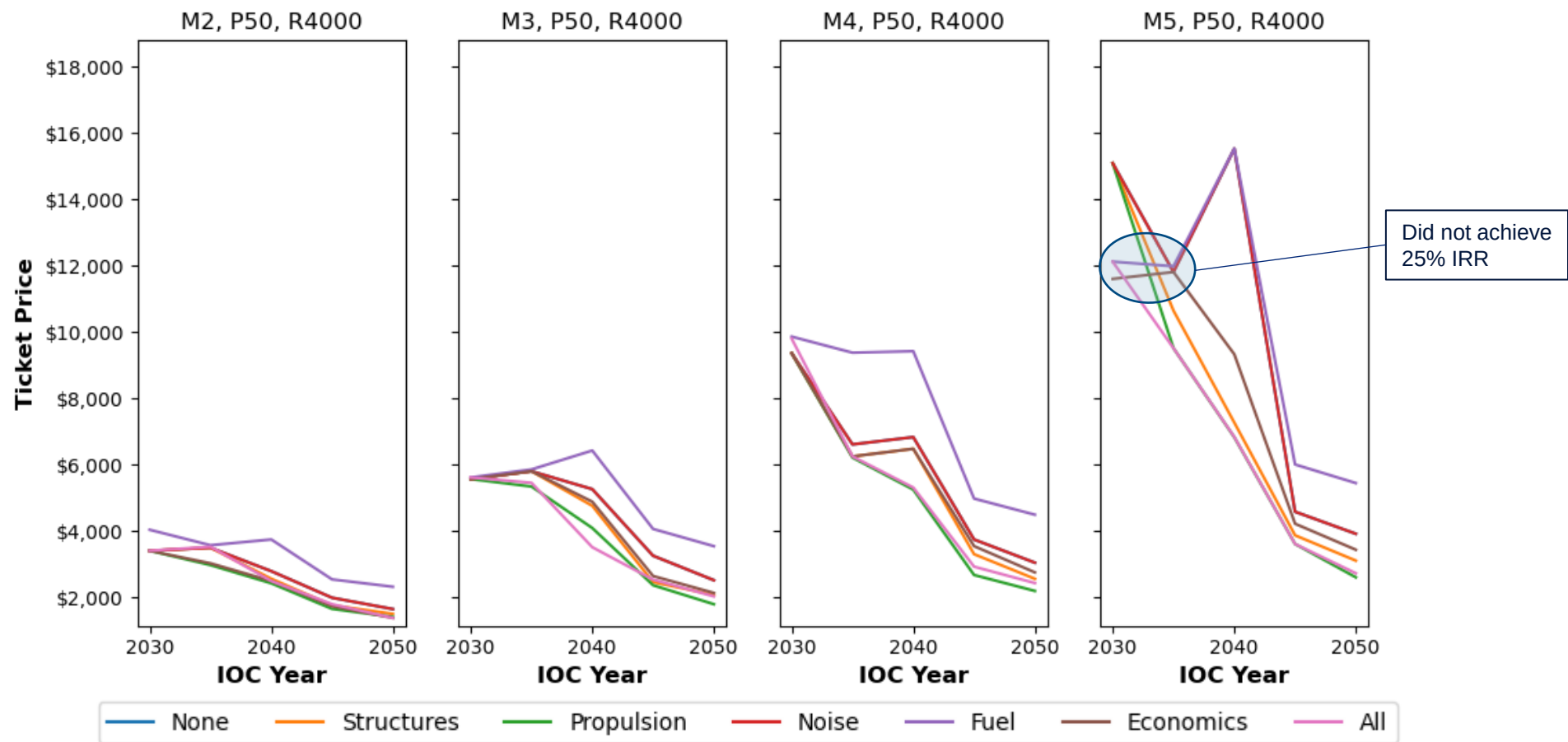
- ▶ Single Aircraft Sensitivity
- ▶ Alternative Fuel Sensitivity

For cases that failed to achieve 25% IRR (albeit, just by a small percentage), delaying IOC enabled these cases to fully achieve 25% IRR



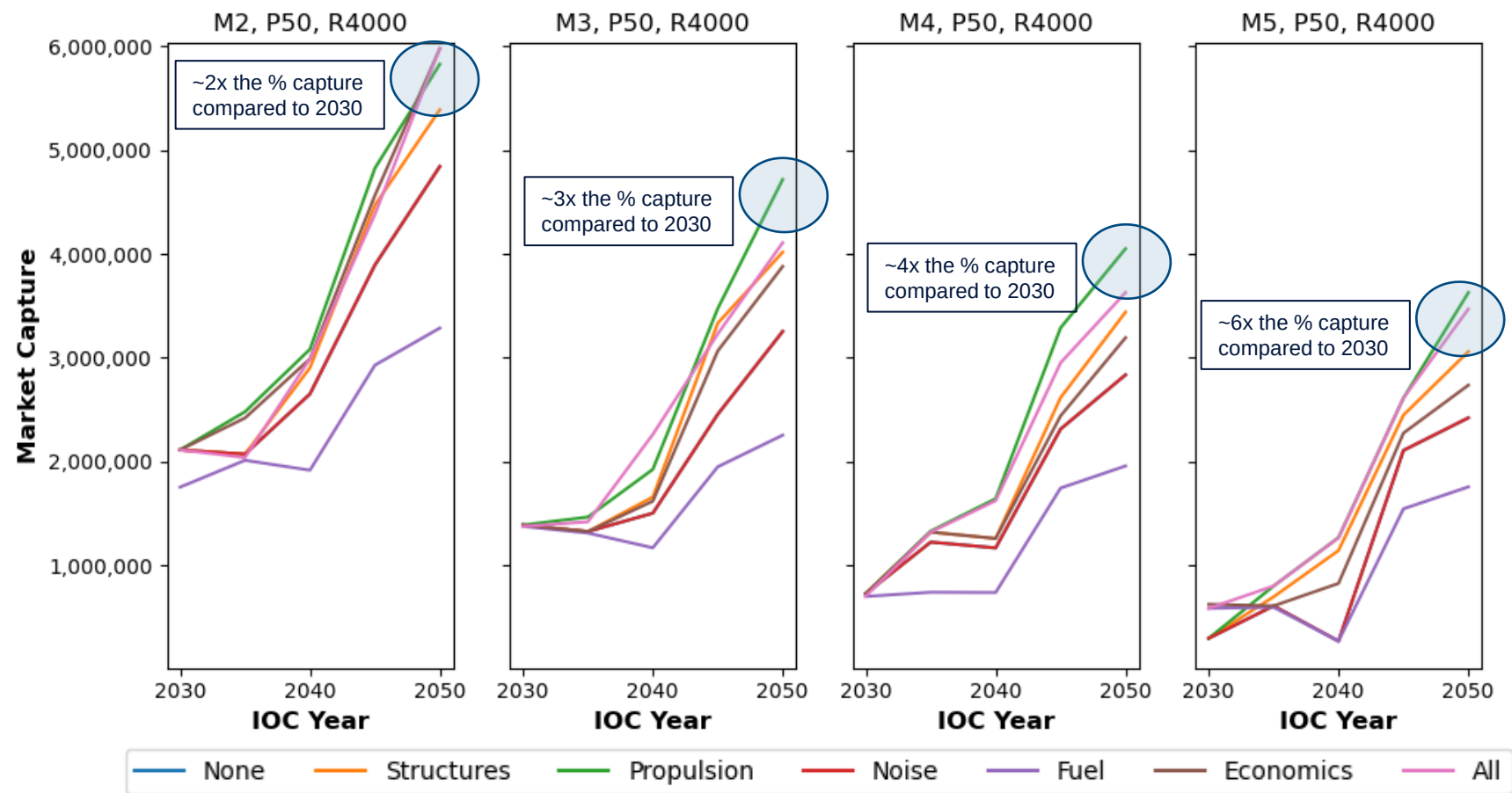
Ticket Price | Jet-A

- ▶ Ticket Prices generally decreased as market size grew and technologies improved
- ▶ Earlier IOC dates for Fuel may see increases due to increased Fuel prices outweighing any benefits



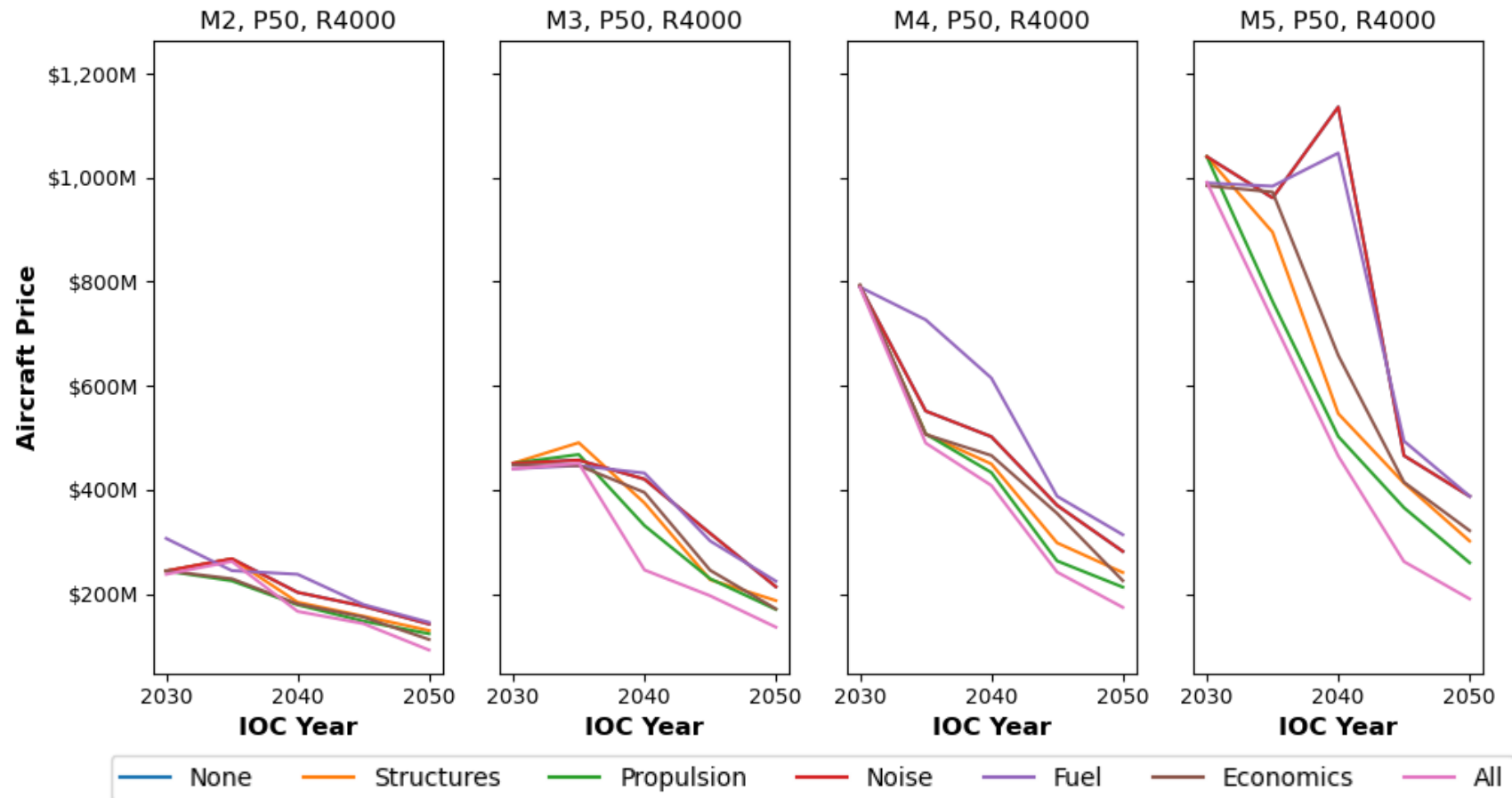
Market Capture | Jet-A

- These values reflect the projected Market Capture at the IOC year (not 2019 numbers)
- Percentage of market capture also improves over time with improved technology



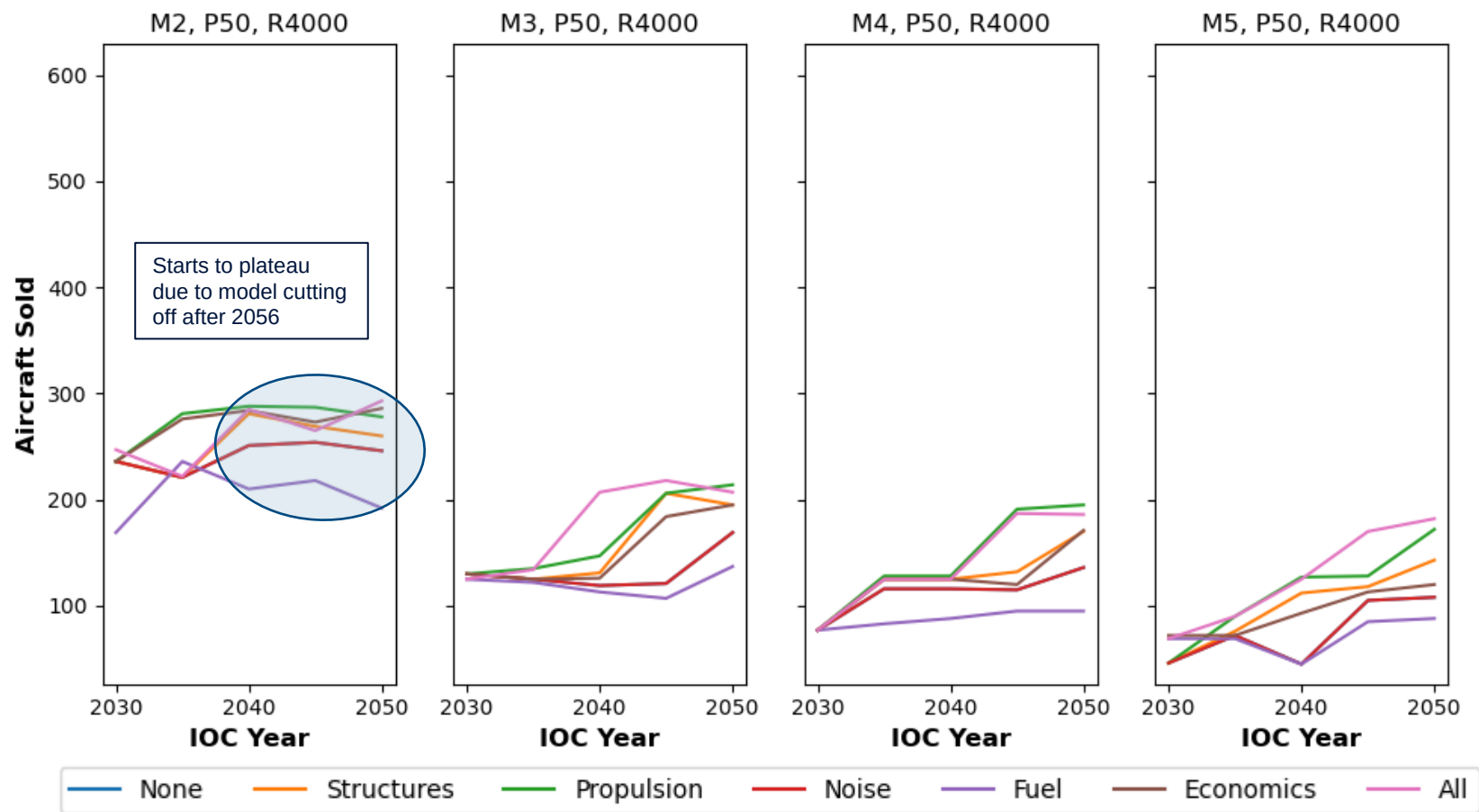
Aircraft Price | Jet-A

- See significant improvements at the higher Mach numbers
- Beyond greater demand capture, Propulsion & Structures improvements are greatest drivers

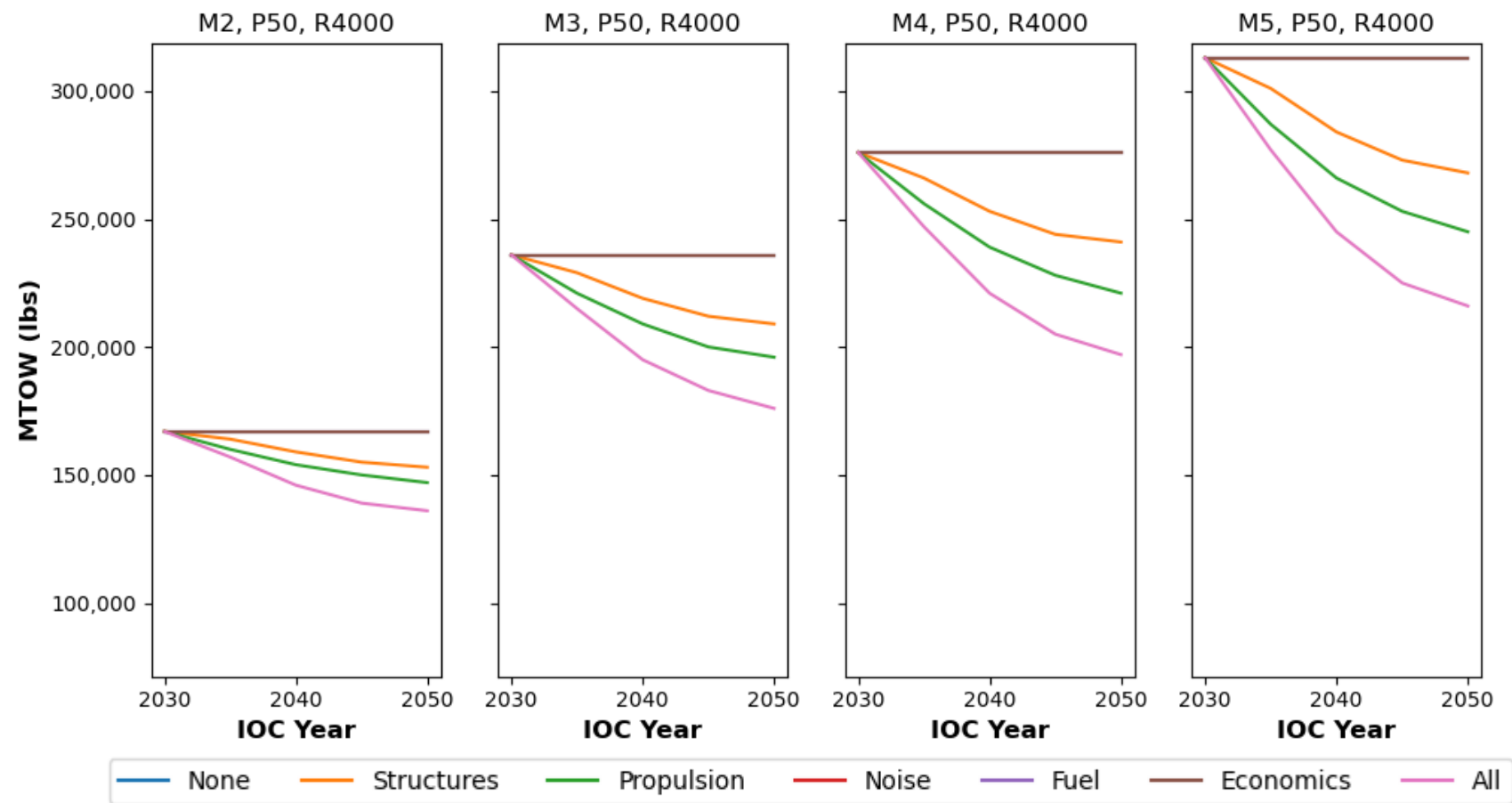


Aircraft Sold | Jet-A

- Initial fleet sizes are greater for later IOC sweeps
- However, with less time available in the model, additional aircraft purchases may not be recognized

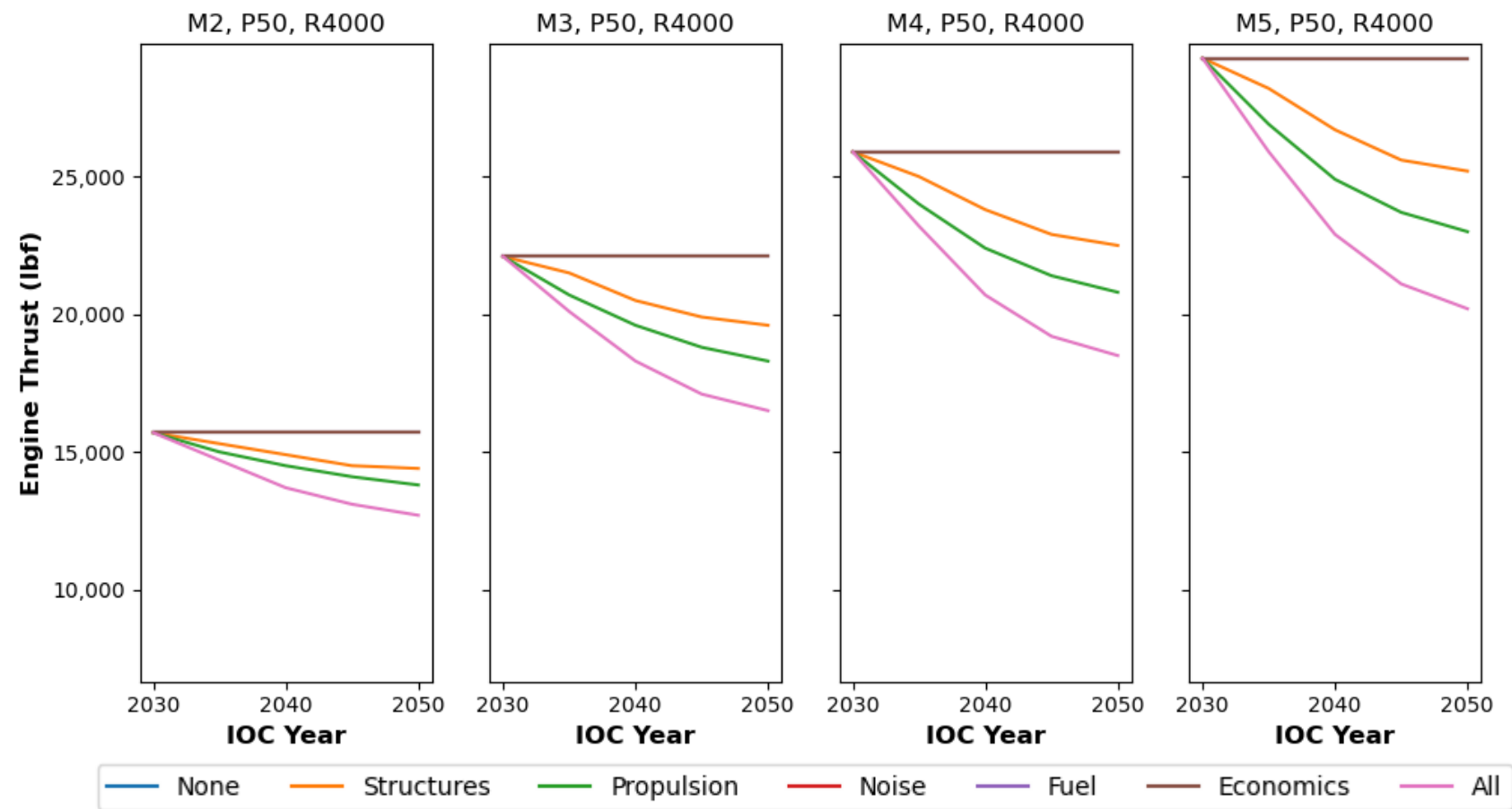


Emphasizes Propulsion being the most impactful as far as technical improvements go

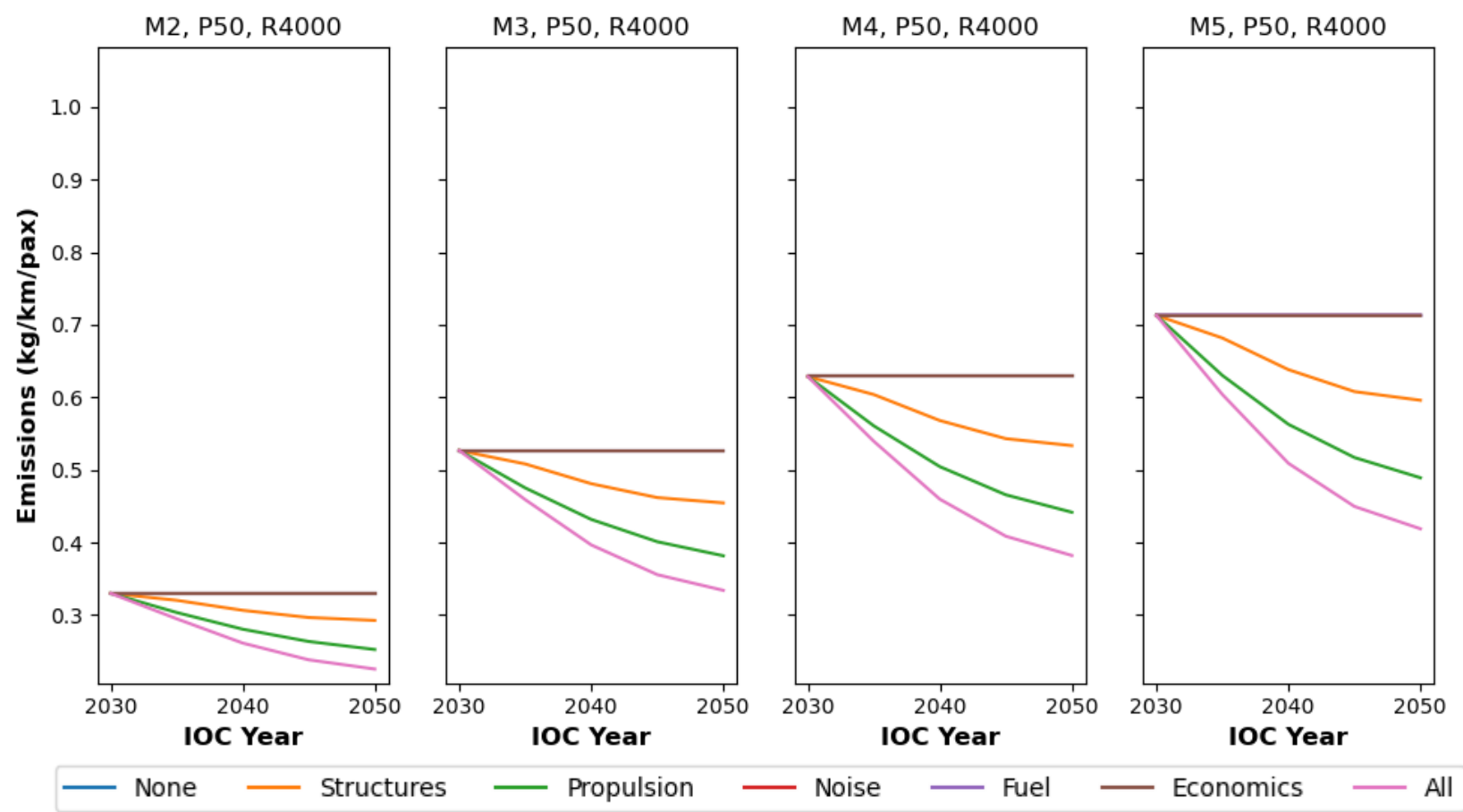


Engine Thrust | Jet-A

Very similar to MTOW but also shows the benefit of Structures improvements on the engine side

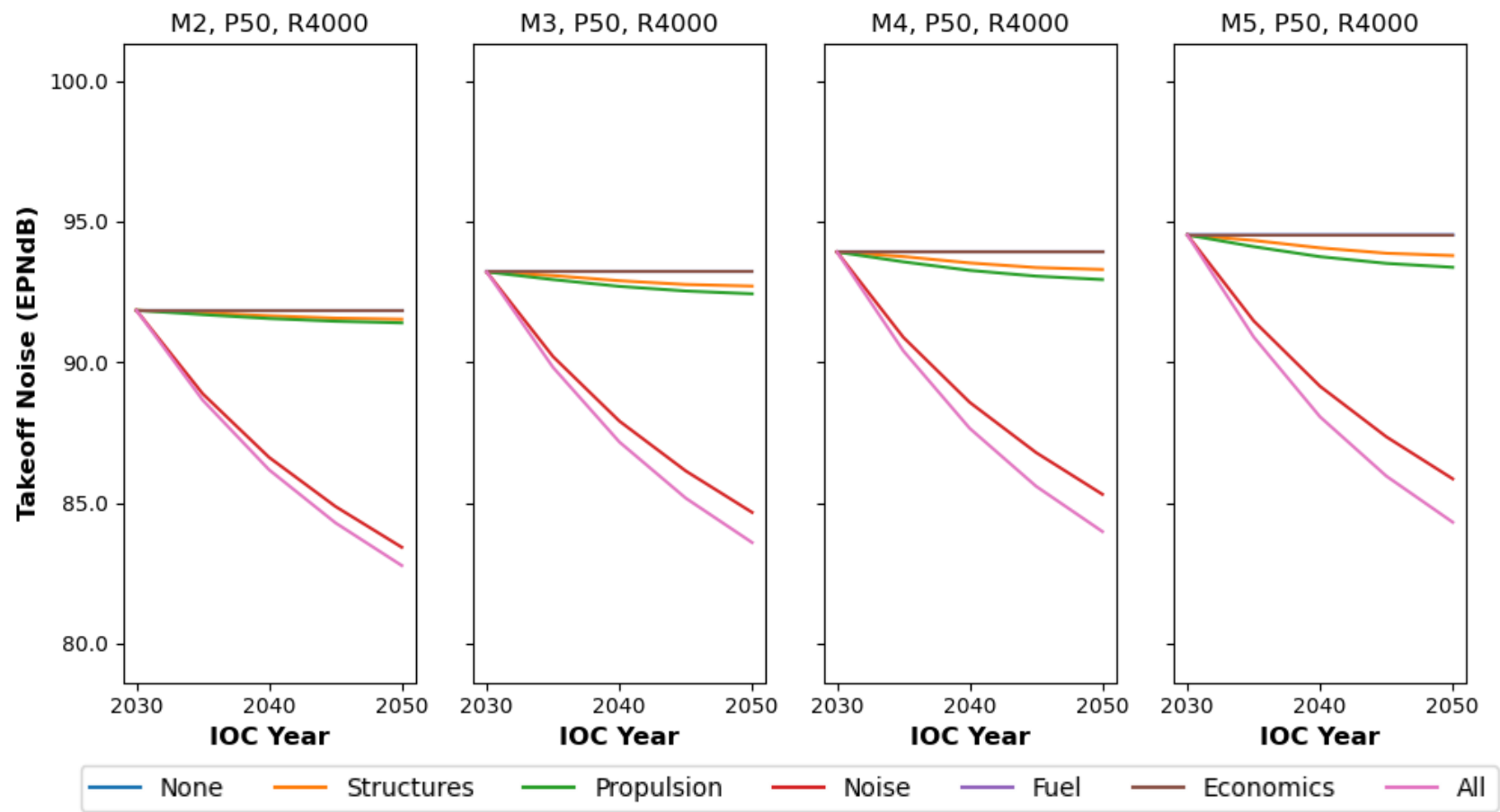


- See improved emissions over time, especially at higher Mach numbers, but still fall above desired levels



Takeoff Noise | Jet-A

- See significant Noise improvements over time as technology improves
- Noise levels drop to be within typical EPNdB ranges of Stage 4 aircraft for Takeoff Noise

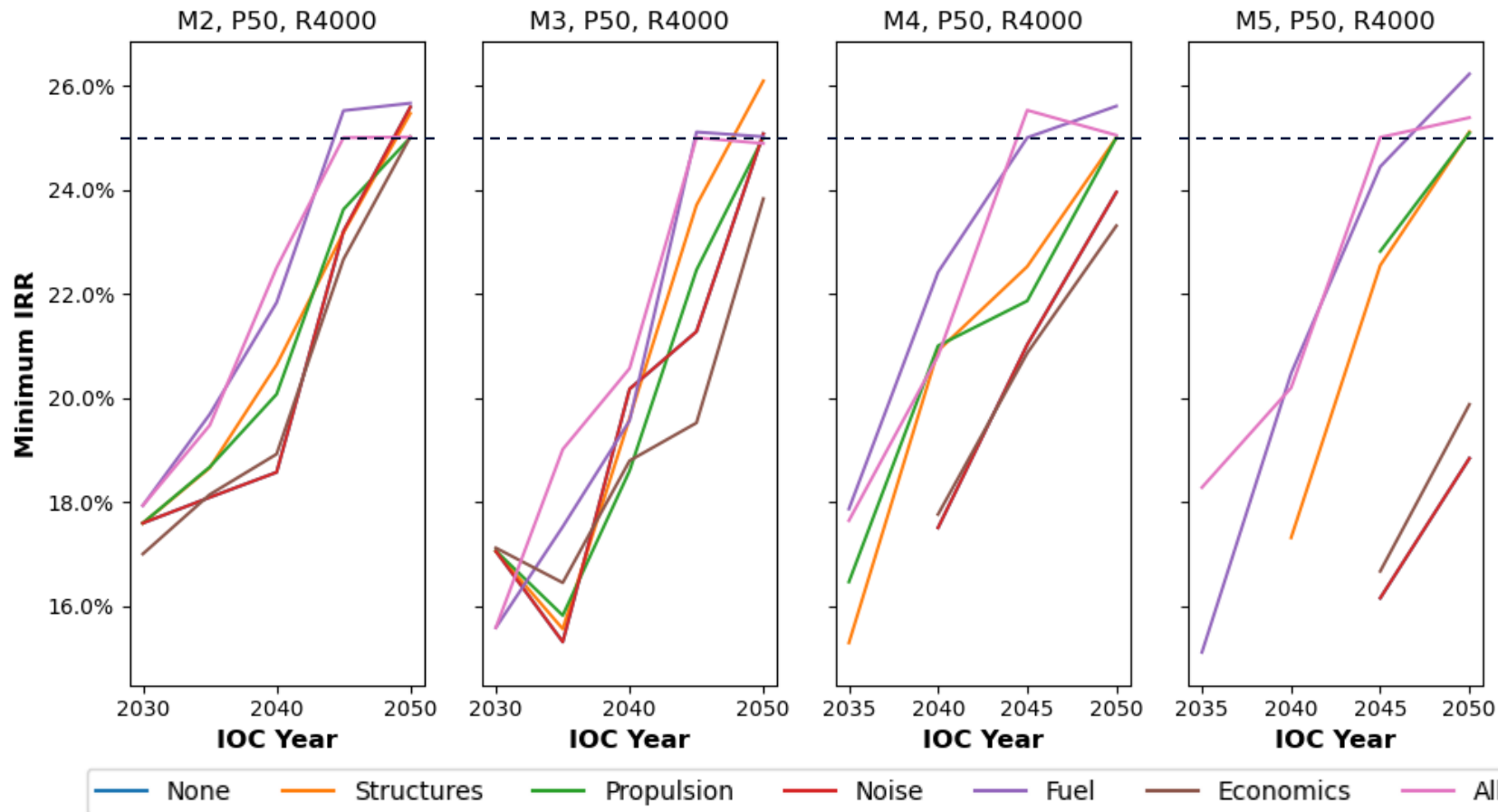


Alternative Fuels Sensitivity

- ▶ **Single aircraft cases were run for SAF, LNG, and LH2**
- ▶ **Trends were mostly consistent with Jet-A cases**
 - The exception here would be with fuel k-factors since SAF & LH2 see prices drop overtime while Jet-A and LNG see prices rise
 - LNG cases start to noticeably fail, losing the fuel price advantage, while SAF and LH2 realize significant cost savings by waiting
- ▶ **Also of note, LH2 cases saw improved IRRs in the out years, achieving the 25% IRR objective after 2040**
 - Design and performance k-factors were the most significant while market growth and macroeconomic improvements weren't as impactful
- ▶ **Full set of plots included in Back-up**

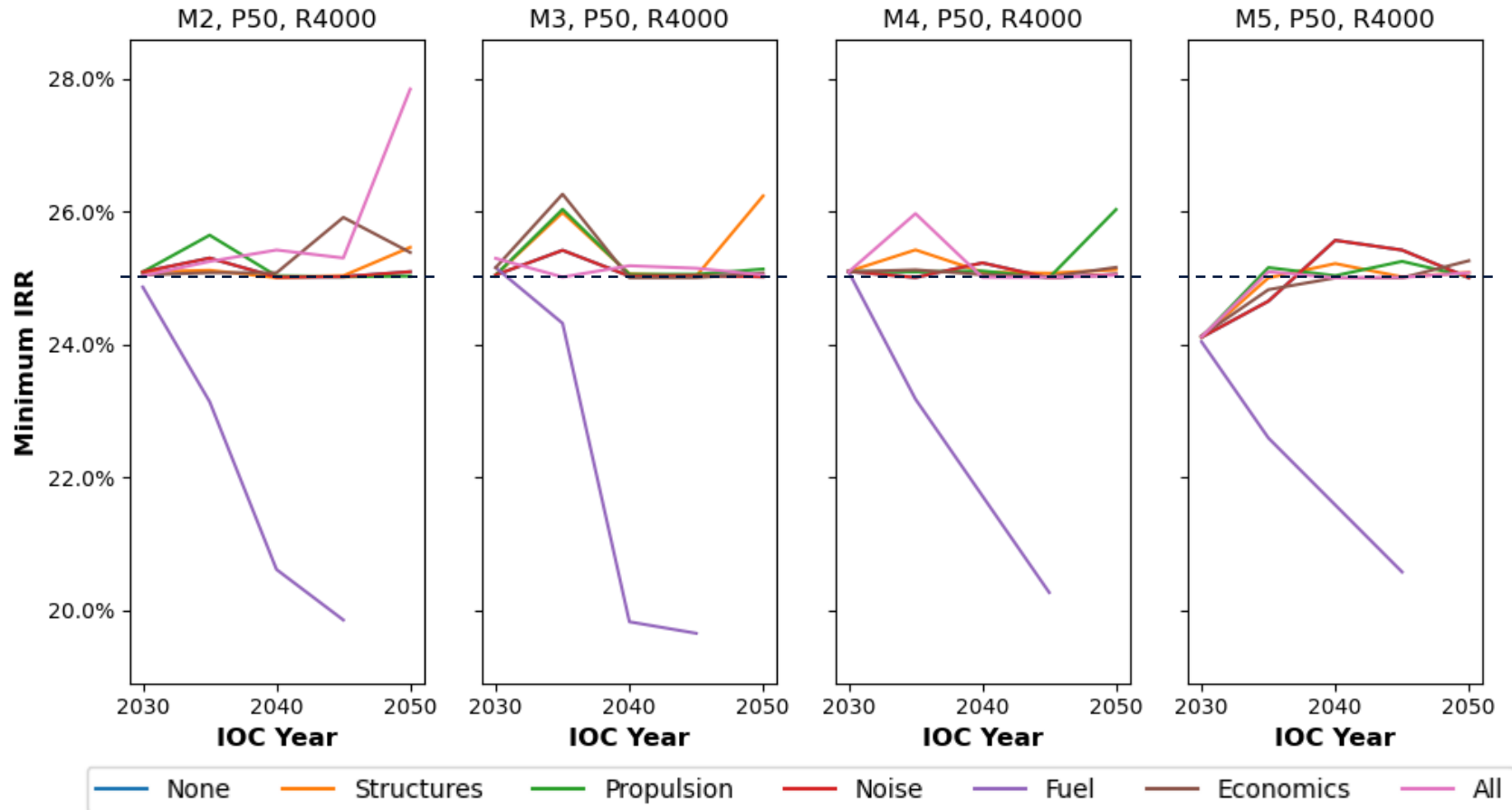
Delayed IOC had a significant impact for LH2 aircraft that achieve 25% IRR with 2045/50 IOC dates

- The significant benefits of improved technology and lower fuel costs are the main contributors



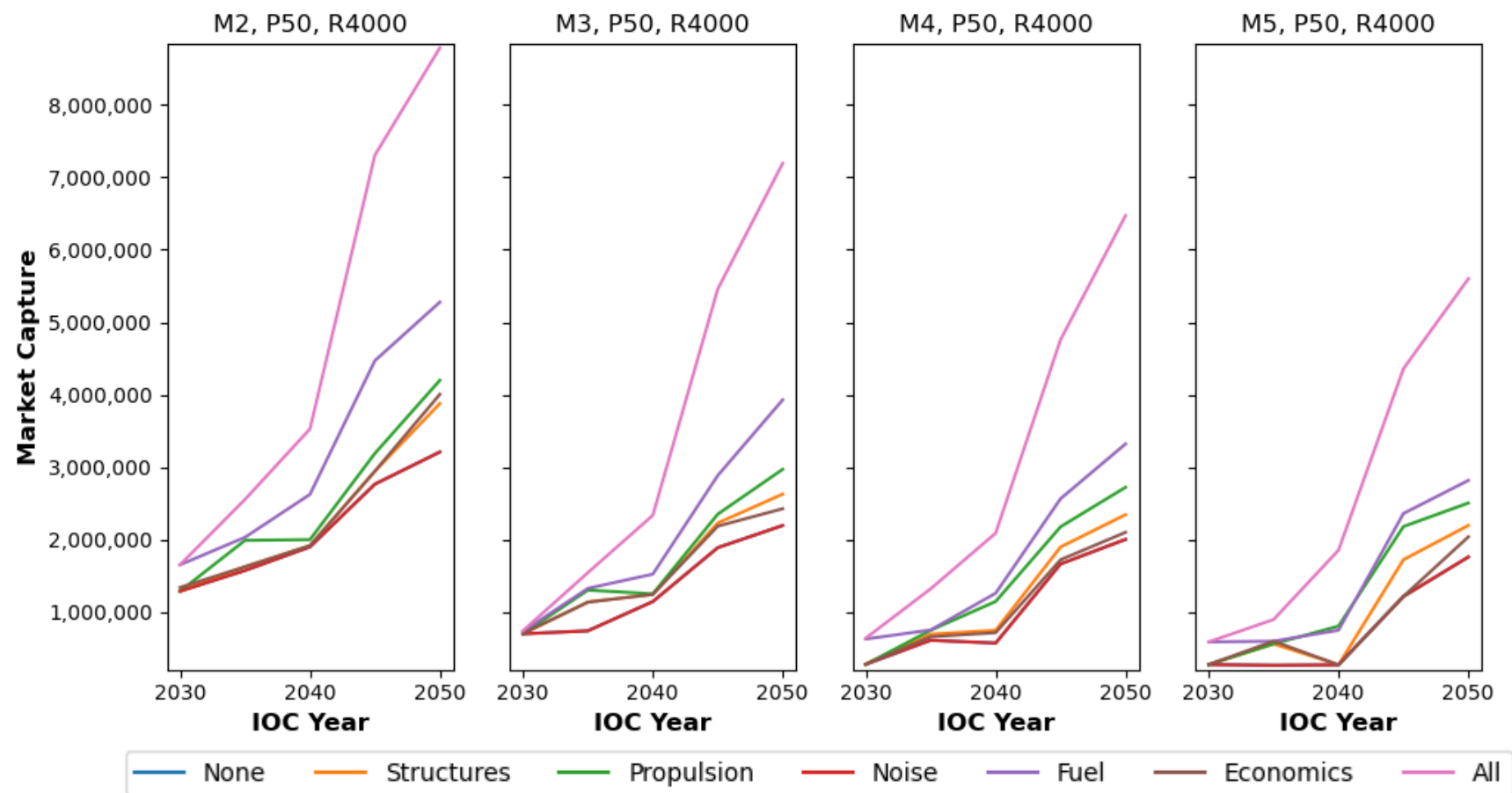
▶ LNG continued to have positive business cases but was adversely affected by rising fuel prices

- This emphasizes the impact of fuel price of cryogenic fuels on the overall business case



Market Capture | SAF

- ▶ For SAF, Market Capture was a better indicator of the impact of lower fuel costs in later years
 - Significant benefits are realized when prices approach Jet-A prices and continue decreasing over time





Conclusions & Takeaways

Conclusions & Takeaways

▤ **Solely allowing the market to grow has a significant impact on the business cases**

- NOTE: This analysis assumed no other players in the market
 - Therefore, the operator and manufacturers were always the first movers and had no competition
 - The full market was available at the start of operations

▤ **Propulsion, Structures, and Economic improvements further improve the business case for Jet-A**

- The technical improvements have a greater impact at higher Mach numbers

▤ **Fuel price k-factors had a noticeable impact on Jet-A but were surmountable while the alternative fuels were more significantly impacted**

- LNG had business cases fail across all Mach numbers as IOC was delayed and fuel prices rose
- SAF was able to significantly reduce ticket price and therefore, capture more demand
- LH2 saw the most benefit in reduced fuel prices
 - Fuel, Propulsion and Structures k-factors all greatly benefitted LH2 and enabled cases to successfully close in the later years

▤ **Mixed fleet cases were improved but still limited by the large development and acquisition costs associated with faster, long-range aircraft**



Final Report Summary

Key Findings – Overall

- ▶ **Overall, when modeling a single Jet-A fueled aircraft type that serves a subset of our 90 candidate transoceanic passenger routes that lie within its unrefueled range, the Mach 2 - 2.5, 4,500-5,500 nmi, and 40-50 passenger aircraft had the best business cases**
 - This conclusion is mostly consistent with the results of the previous market study conducted with the Deloitte Team, but slightly revised due to changes in the model and objective function we currently used
 - Slightly larger aircraft than before, as larger aircraft reduce ticket prices and capture more of the traveling public

- ▶ **Our overall position is unchanged from our prior study. We believe that there are viable economic markets for future high-speed (supersonic and hypersonic) aircraft**

- ▶ **However, we acknowledge that safety, noise compliance, emission, compliance, and sonic boom remain significant challenges to this industry. While our simulations report environmental variables as outputs for each case, we did not attempt to restrict our design space based on current government guidance or regulations on exhaust emissions or takeoff noise. Doing so will certainly reduce, or even eliminate, the viable options for high-speed commercial flight. Additional research is needed in these areas.**

Key Findings – Mixed Fleet

▶ **Mixed fleet based on short- and long-range segregated aircraft types not the best approach**

- Only marginally improved annual passenger capture
- Resulted in poorer than anticipated business cases for the long-range aircraft type due to low production rates, high ticket prices, and reduced demand. It lost most of the prior market to the new short-range aircraft
- Lesson learned: we need to take another look at this mixed-fleet simulation so that both aircraft types are used more effectively

▶ **Recommend assessing a mixed fleet solution based on route demand and/or density**

- A larger aircraft operating on high density routes (e.g. NYC – LHR) and a smaller one for low density markets could capture more routes, increase load factors, and allow higher utilization rates of both aircraft types, even if those two aircraft types might have similar maximum ranges
- Likely generates a more robust solution for both aircraft manufacturers as well
- Recommended for future investigation with our DES model

Key Findings – Alternative Fuels

▶ **SAF and Jet-A were very similar in terms of economic and airplane performance**

- SAF is currently much more expensive than Jet-A. Gap is expected to narrow over time as the SAF supply chain scales and Jet-A prices increase
- SAF will become a viable alternative fuel as the price continues to decrease due to its status as net-zero carbon fuel
- We conclude that SAF the preferred long-term solution for high-speed aircraft applications, but we recognize that the significant investment in production and distribution infrastructure is a major barrier to adoption and it was not modeled here

▶ **LNG produced some of the best business cases, but...**

- Lower initial fuel price relative to Jet-A and improved energy density are good
- But, LNG yields higher aircraft dev and manufacturing costs due to additional complexity and larger tanks (less density fuel)
- LNG burns cleaner than Jet-A but is still a carbon producer. Sustainability might be an issue as LNG prices increase

▶ **LH2 struggled to achieve the required 25% IRR in most of the trade space**

- High performance but low density meant very high onboard volumes of fuel – increasing aircraft size and drag
- High operator fuel costs and high aircraft prices make LH2 business cases hard to justify for most of the trade space
- Only at Mach 2, were our simulated overland LH2 aircraft able to achieve 25% IRR at 3,000 nmi and 3,500 nmi ranges
- We conclude that short range LH2 aircraft are feasible and may be viable options for domestic routes

Key Findings – Overland Routes

▶ **Addition of overland routes significantly boosts the available market and demand**

- We did not address “how” overland sonic boom restrictions might be eliminated. This is a highly complex political and environmental issue. Rather, we simply assumed that they were in order to simulate the inclusion of a much larger number of potential supersonic routes as a bounding case on high-speed flight
- The impact of overland flight on the model is significant and the number of passengers participating in supersonic / hypersonic flight annually increases by ~10X compared to our transoceanic baseline model
- Initial capital outlays could be a financial hurdle for operators and manufacturers, but a controlled service rollout might mitigate the capital needs and benefit all stakeholders

▶ **High production volumes solidify the manufacturers’ business cases**

- Number of aircraft produced could increase from less than 200 to nearly 1000 aircraft in certain simulations

▶ **Operator’s business case also improved**

- Optimal aircraft size can increase (to 88 pax), and ticket prices can be reduced while still meeting the 25% IRR
- Increased upfront acquisition costs are needed to address the high demand, but controlled service rollout might mitigate the capital needs and benefit all stakeholders

Key Findings – IOC Dates

▶ All the considered technology sets offered improvements in the study metrics over time

- Assuming that no competitors will enter the market first, simply waiting for the increase in the elite air travel market size and leveraging advancements in technology is a preferred strategy. However, waiting might not be possible
- SAF will become a viable alternative fuel as the price continues to decrease due to its status as net-zero carbon fuel

▶ Propulsion performance and air travel market growth offered the most benefits in economics

- Propulsion technologies have the potential to improve engine Isp, lower engine weight (and therefore aircraft weight), reduce emissions, reduce engine maintenance costs, and reduce noise
- Structures and noise reduction technologies were also valuable in a government technology investment portfolio

▶ Fuel prices significantly influence the business cases for alternative fuels

- Jet-A and LNG prices are expected to increase over time, while SAF and LH2 prices are expected to become more competitive over time (assuming that production and distribution infrastructures advance as assumed)
- We recommend baselining SAF for future high-speed aircraft, while continuing to evaluate LNG and LH2, especially for the highest speed aircraft whose ramjet or scramjet propulsion systems may require the fuels

Recommendations

1. NASA and FAA continue their efforts to permit overland supersonic flight

- Drastically increased market size
- More robust business cases for supersonic / hypersonic developers and operators

2. In the meantime, a two-phased “leader-follower” compromise strategy for government and commercial

- Small fast first-to-market transoceanic “leader” aircraft
- Larger slower “follower” aircraft designed for additional overland routes
- Delays action on supersonic overland flight and reduces near-term capital requirements

3. Continued investments in supersonic and hypersonic propulsion technology, particularly in the areas of:

- Engine fuel efficiency and emissions
- Takeoff noise
- Engine maintenance costs
- Engine weight

4. Continued investment in SAF with further exploration of LNG and LH2 viability

- Supply of all alternative fuels needs to be orders of magnitudes greater
- LNG shows promise while LH2 is economically viable for some simulated solutions



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Backup Slides

▶ Technical k-factors:

Structures k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Structures Mass Reduction	Mass	0%	-4%	-7%	-9%	-11.0%	-12.5%
TPS Mass Reduction	Mass	0%	-4%	-7.5%	-10.0%	-12.5%	-14.5%
L/D	L/D	0%	1%	3%	5%	6.0%	7.0%

Propulsion k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Engine T/W	T/W	0%	4.0%	8%	11.5%	13.5%	15.5%
Isp	Fuel Eff.	0%	2.5%	5%	7.0%	8.5%	10%
Emissions	CO2e	0%	-2.5%	-4.0%	-7.0%	-8.0%	-9.0%

Noise k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Sideline Noise	Takeoff Noise	0%	-3.0%	-6.0%	-7.0%	-9.0%	-10.0%
Overpressure	Overpressure	0%	-9.0%	-13.5%	-15.0%	-21.5%	-22.5%

▶ Economic k-factors:

Fuel k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
Jet-A Prices	Fuel Cost	0%	9.0%	15.5%	27.5%	42.5%	53.0%
LNG Prices	Fuel Cost	0%	0.0%	2.5%	4.5%	8.0%	13.5%
SAF Prices	Fuel Cost	0%	-12.0%	-21.0%	-29.0%	-42.0%	-45.5%
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Economic k-factors	Directly Impacts	2030 (base year)	2035	2040	2045	2050	2055
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Engine Manufacturing	TFU	0%	-6.5%	-10.5%	-14.5%	-19.5%	-26.0%
Tax Benefits / Detriments	Cost	0%	-7%	-5.0%	-3.5%	-2.5%	-2.0%

Airports

AIRPORT	AIRPORT NAME	ROUTES
ATL	Atlanta (GA) – Hartsfield-Jackson Atlanta International Airport	Domestic & International
DFW*	Dallas/Ft. Worth (TX) - Dallas/Fort Worth International	Domestic & International
DEN*	Denver (CO) - Denver International Airport	Domestic & International
ORD*	Chicago (IL), O'Hare International Airport	Domestic & International
LAX	Los Angeles (CA) - International	Domestic & International
CLT	Charlotte (NC)	Domestic & International
MCO	Orlando - International Airport (FL)	Domestic & International
LAS*	Las Vegas (NV)	Domestic & International
PHX*	Phoenix (AZ) - Sky Harbor International	Domestic & International
MIA	Miami (FL)	Domestic & International
SEA	Seattle/Tacoma (WA)	Domestic & International
IAH*	Houston, TX - George Bush Intercontinental Airport	Domestic & International
JFK	New York - John F. Kennedy (NY)	Domestic & International
EWR	New York - Newark (NJ)	Domestic & International
FLL*	Fort Lauderdale/Hollywood (FL)	Domestic & International
MSP*	Minneapolis - St. Paul International Airport (MN)	Domestic & International

*New airport to model for Overland Route Sensitivity Study

Airports

AIRPORT	AIRPORT NAME	ROUTES
SFO	San Francisco - International Airport, SA	Domestic & International
DTW*	Detroit (MI) , Wayne County Airport	Domestic & International
BOS	Boston (MA) - General Edward Lawrence Logan	Domestic & International
SLC*	Salt Lake City (UT)	Domestic & International
PHL	Philadelphia (PA) - International	Domestic & International
BWI*	Baltimore (MD) - Washington International Airport	Domestic & International
TPA*	Tampa - International (FL)	Domestic & International
SAN*	San Diego - Lindberg Field International (CA)	Domestic & International
LGA*	New York - LaGuardia (NY)	Domestic & International
MDW*	Chicago (IL), Midway	Domestic & International
BNA*	Nashville (TN)	Domestic & International
IAD	Washington DC - Dulles International	Domestic & International
DAL*	Dallas (TX) , Love Field	Domestic Only
DCA*	Washington DC - Ronald Reagan National	Domestic Only
PDX*	Portland International (OR)	Domestic Only
AUS*	Austin (TX) - Austin-Bergstrom Airport	Domestic Only

*New airport to model for Overland Route Sensitivity Study

Airports

AIRPORT	AIRPORT NAME	ROUTES
HOU*	Houston (TX) , Hobby	Domestic Only
HNL*	Honolulu (HI) - Honolulu International Airport	Domestic Only
STL*	St. Louis (MO) Lambert–St. Louis International Airport	Domestic Only
RSW*	Fort Myers, Southwest Florida Reg (FL)	Domestic Only
SMF*	Sacramento (CA)	Domestic Only
MSY*	New Orleans, La	Domestic Only
SJU*	San Juan - Luis Munoz Marin International Airport	Domestic Only
RDU*	Raleigh/Durham (NC)	Domestic Only
SJC*	San Jose (CA)	Domestic Only
OAK*	Oakland (CA)	Domestic Only
MCI*	Kansas City (MO) - Kansas City International Airport	Domestic Only
CLE*	Cleveland (OH) - Cleveland Hopkins International	Domestic Only
IND*	Indianapolis (IN) International	Domestic Only
SAT*	San Antonio (TX)	Domestic Only
SNA*	Orange County (Santa Ana) (CA)	Domestic Only
PIT*	Pittsburgh International Airport (PA)	Domestic Only

*New airport to model for Overland Route Sensitivity Study

Airports

AIRPORT	AIRPORT NAME	ROUTES
CVG*	Cincinnati (OH) - Cincinnati/Northern Kentucky Int'l	Domestic Only
CMH*	Columbus (OH) - Port Columbus International	Domestic Only
PBI*	West Palm Beach (FL)	Domestic Only
JAX*	Jacksonville (FL) - International	Domestic Only
MKE*	Milwaukee (WI)	Domestic Only
ONT*	Ontario (CA)	Domestic Only
ANC*	Anchorage (AK) - Ted Stevens Anchorage International	Domestic Only
BDL*	Hartford (CT) /Springfield (MA)	Domestic Only
OGG*	Kahului (HI)	Domestic Only
BUR*	Burbank (CA)	Domestic Only
OMA*	Omaha (NE)	Domestic Only
MEM*	Memphis (TN)	Domestic Only
BOI*	Boise (ID) - Boise Air Terminal	Domestic Only
RNO*	Reno (NV)	Domestic Only
CHS*	Charleston (SC)	Domestic Only
OKC*	Oklahoma City (OK) - Will Rogers World	Domestic Only

*New airport to model for Overland Route Sensitivity Study

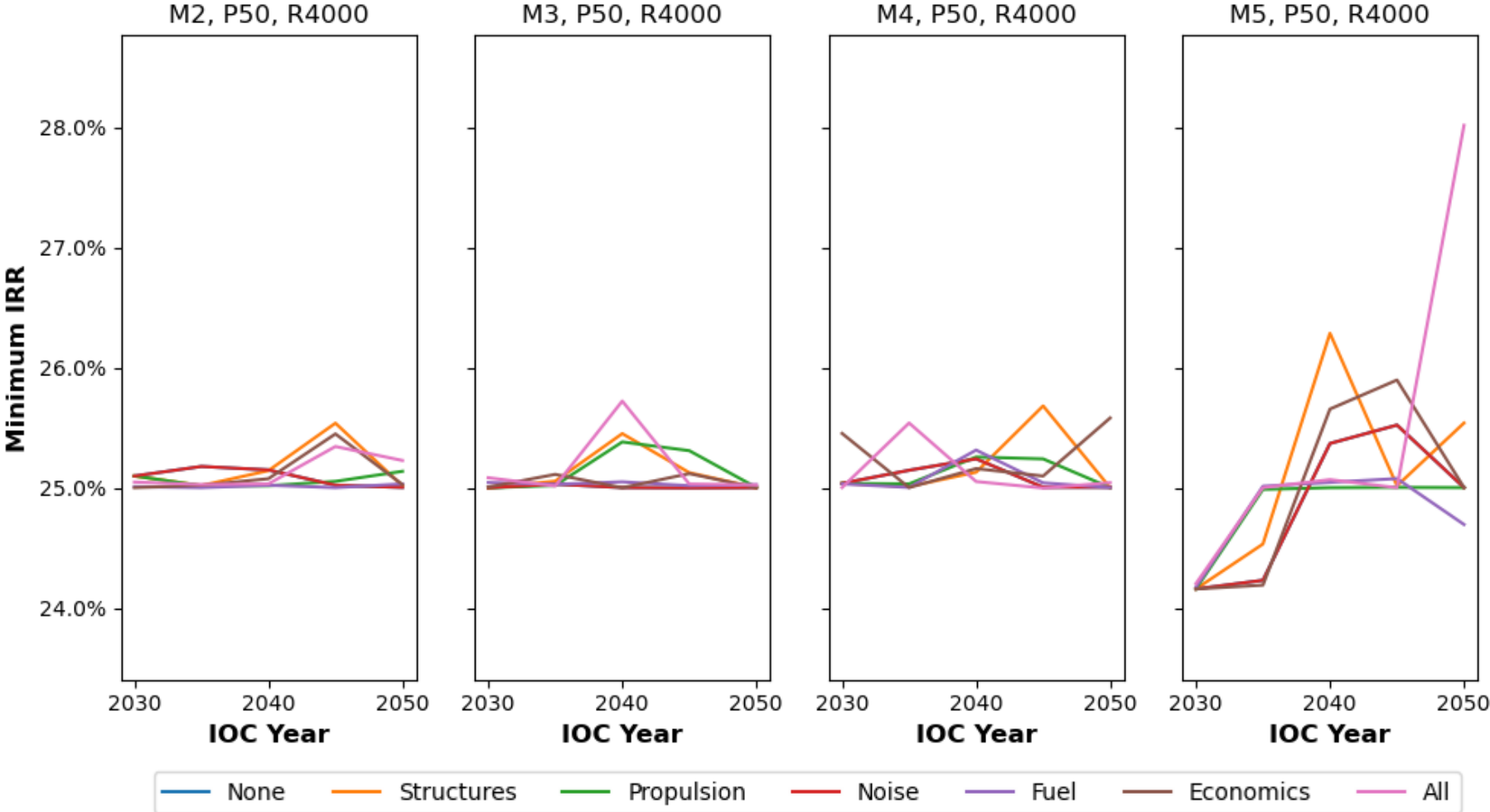


IOC Alternative Fuels

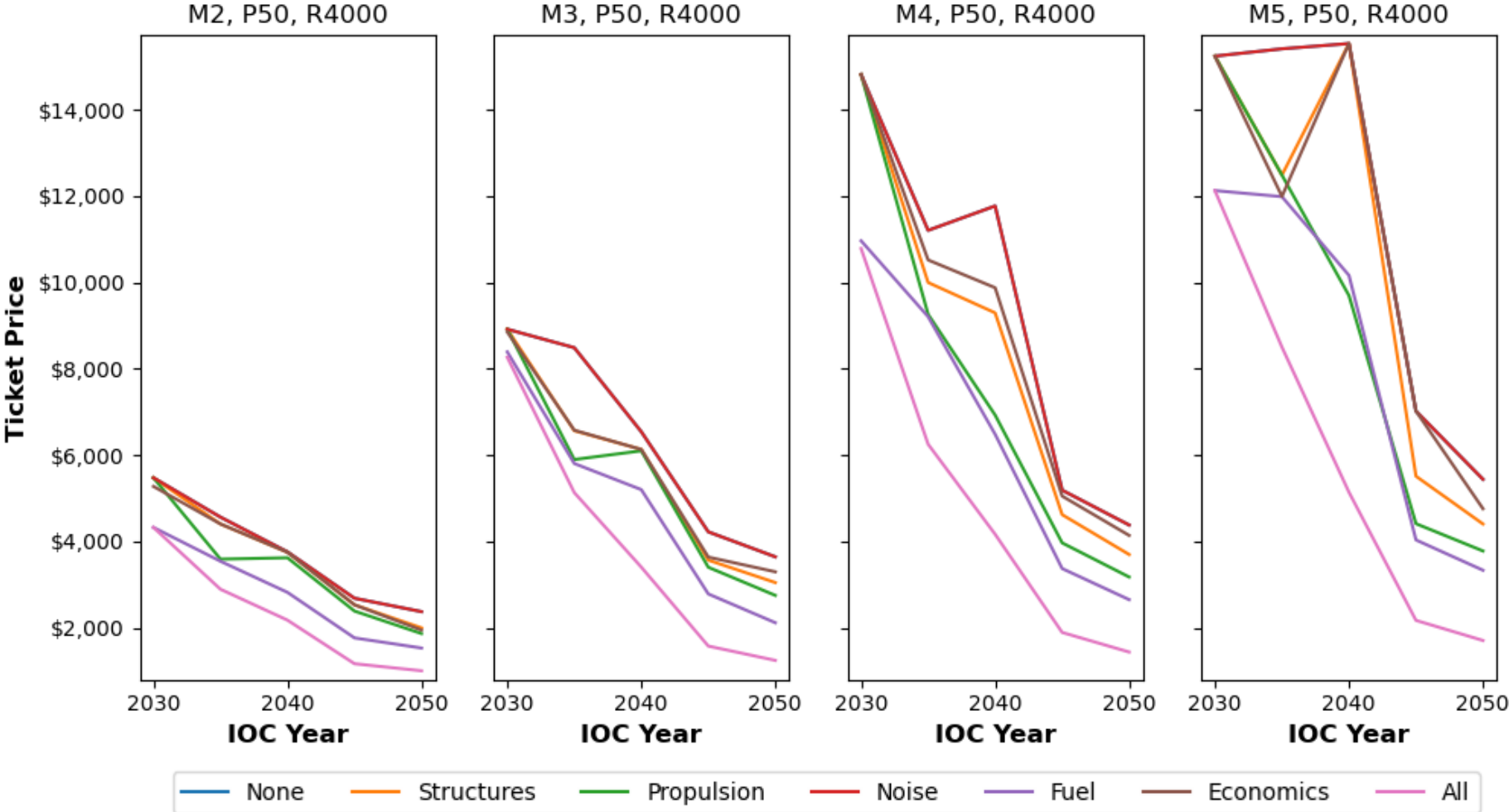
- ▷ SAF
- ▷ LNG
- ▷ LH2



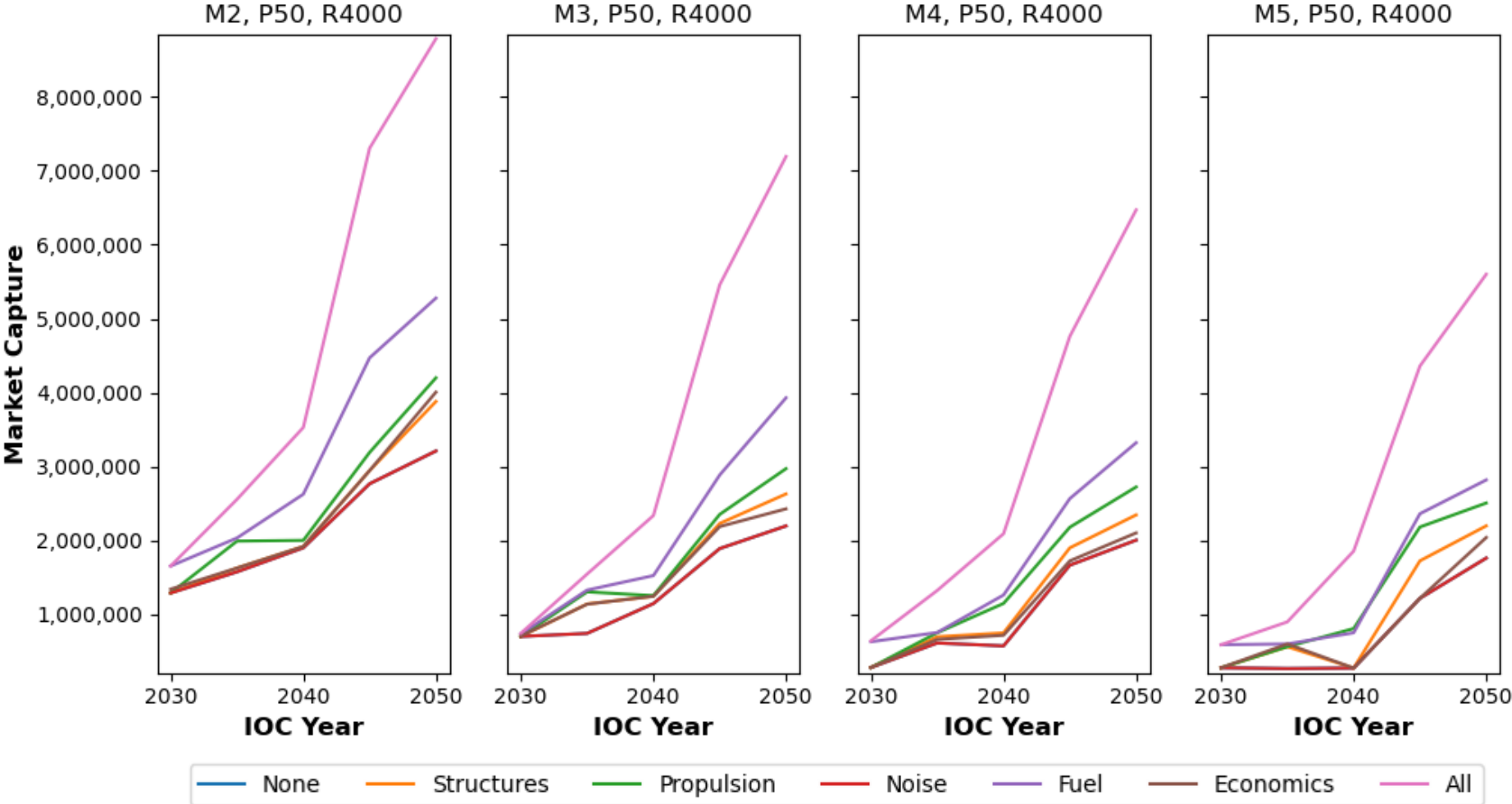
SAF

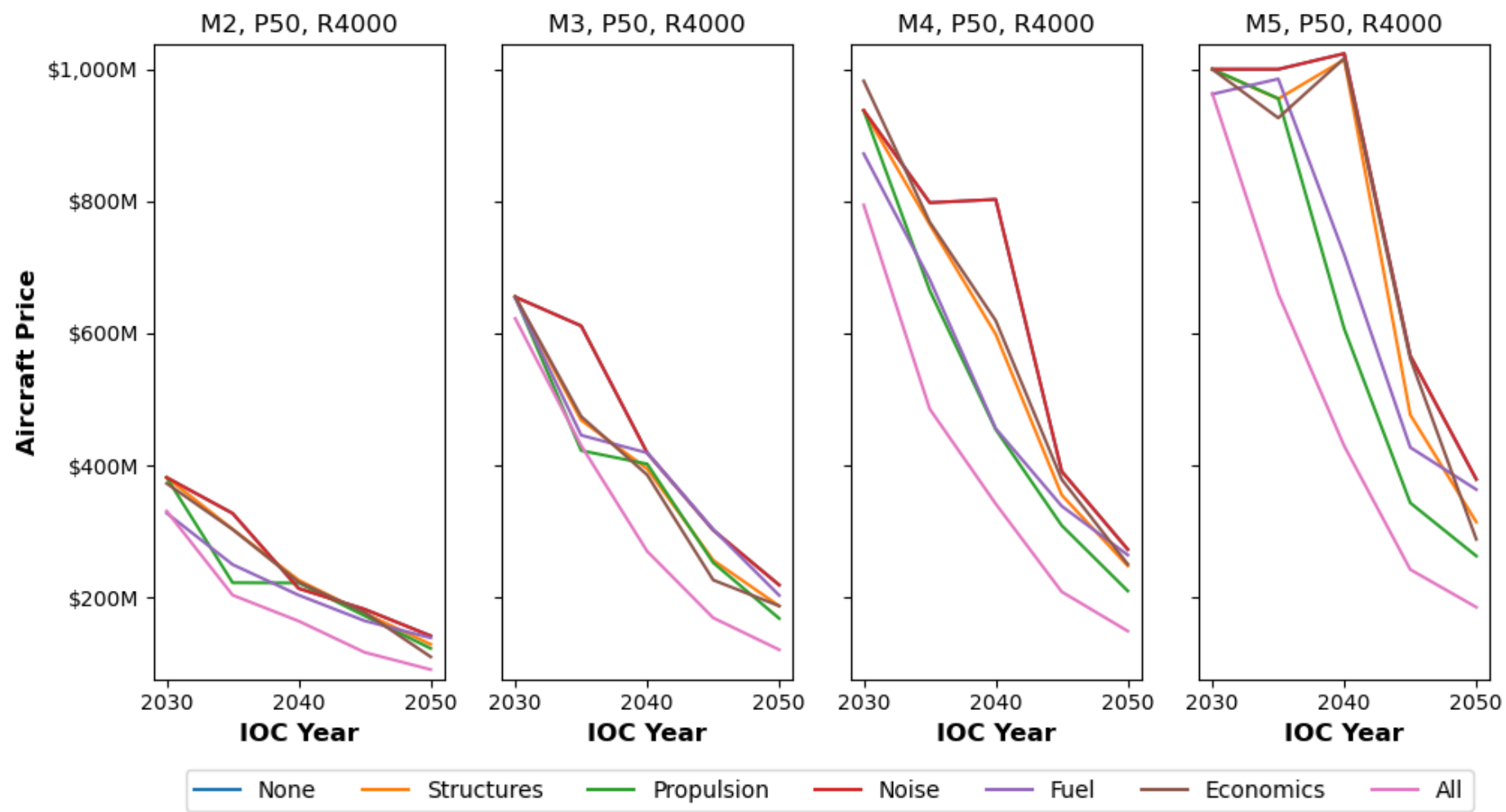


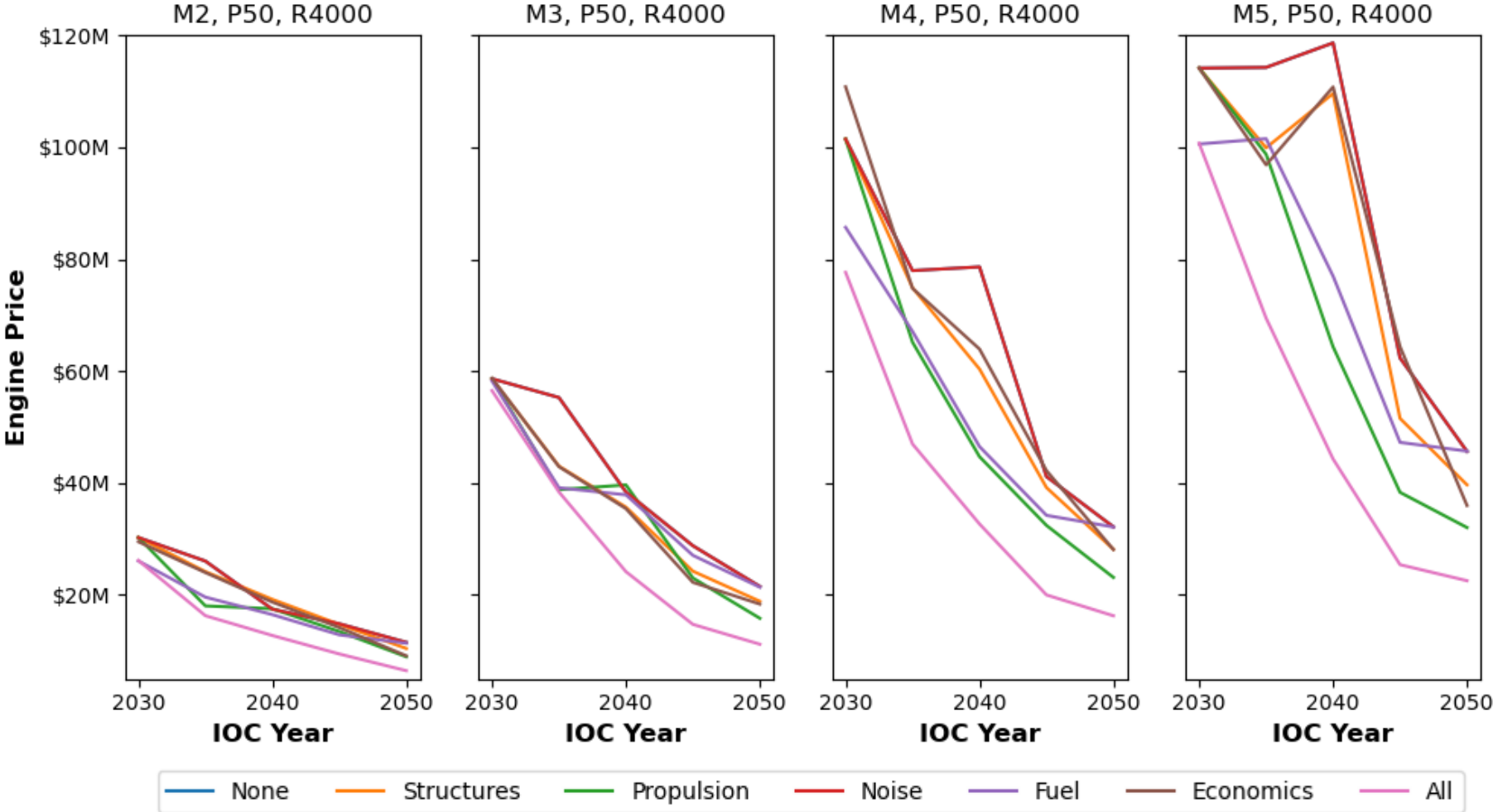
Ticket Price | SAF

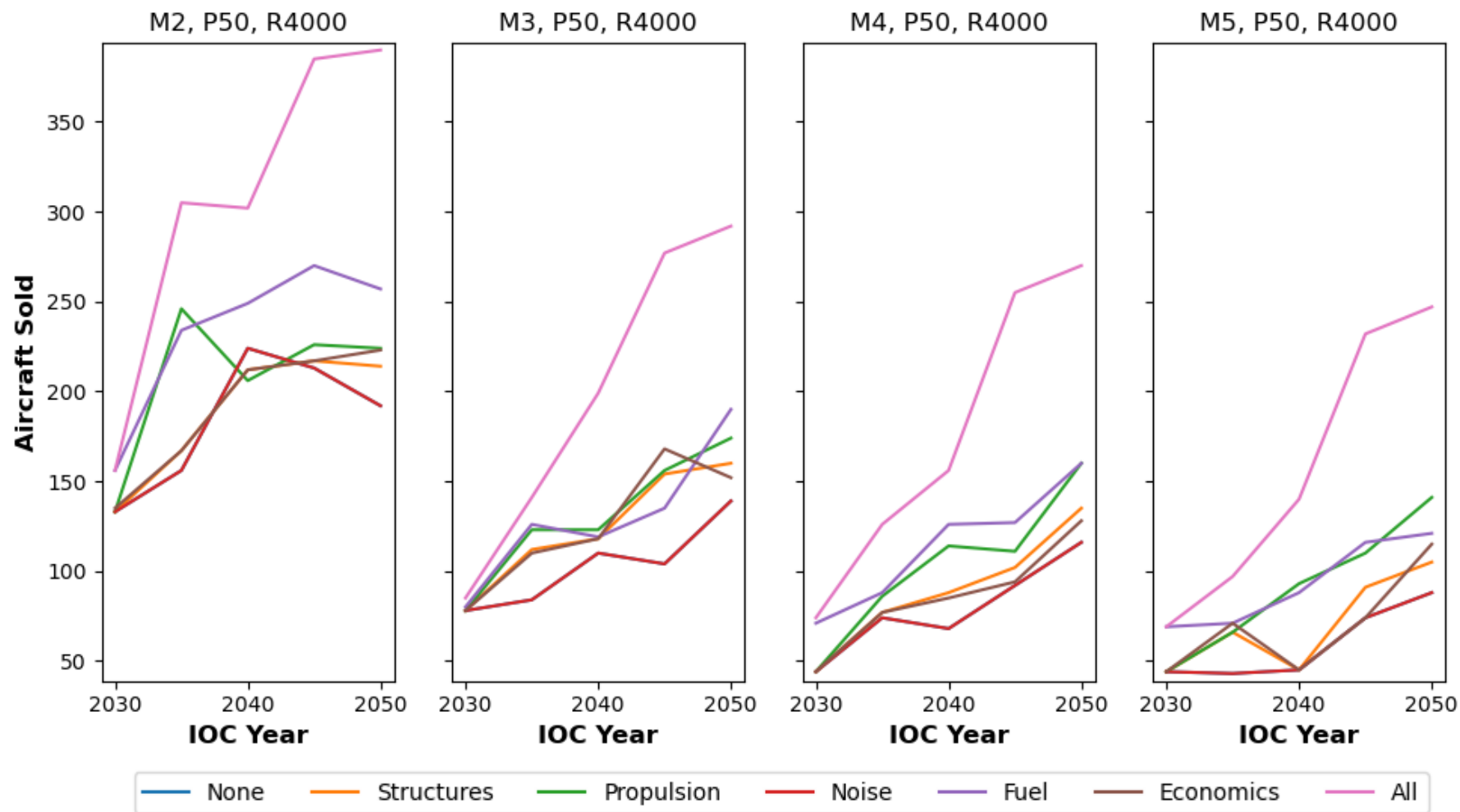


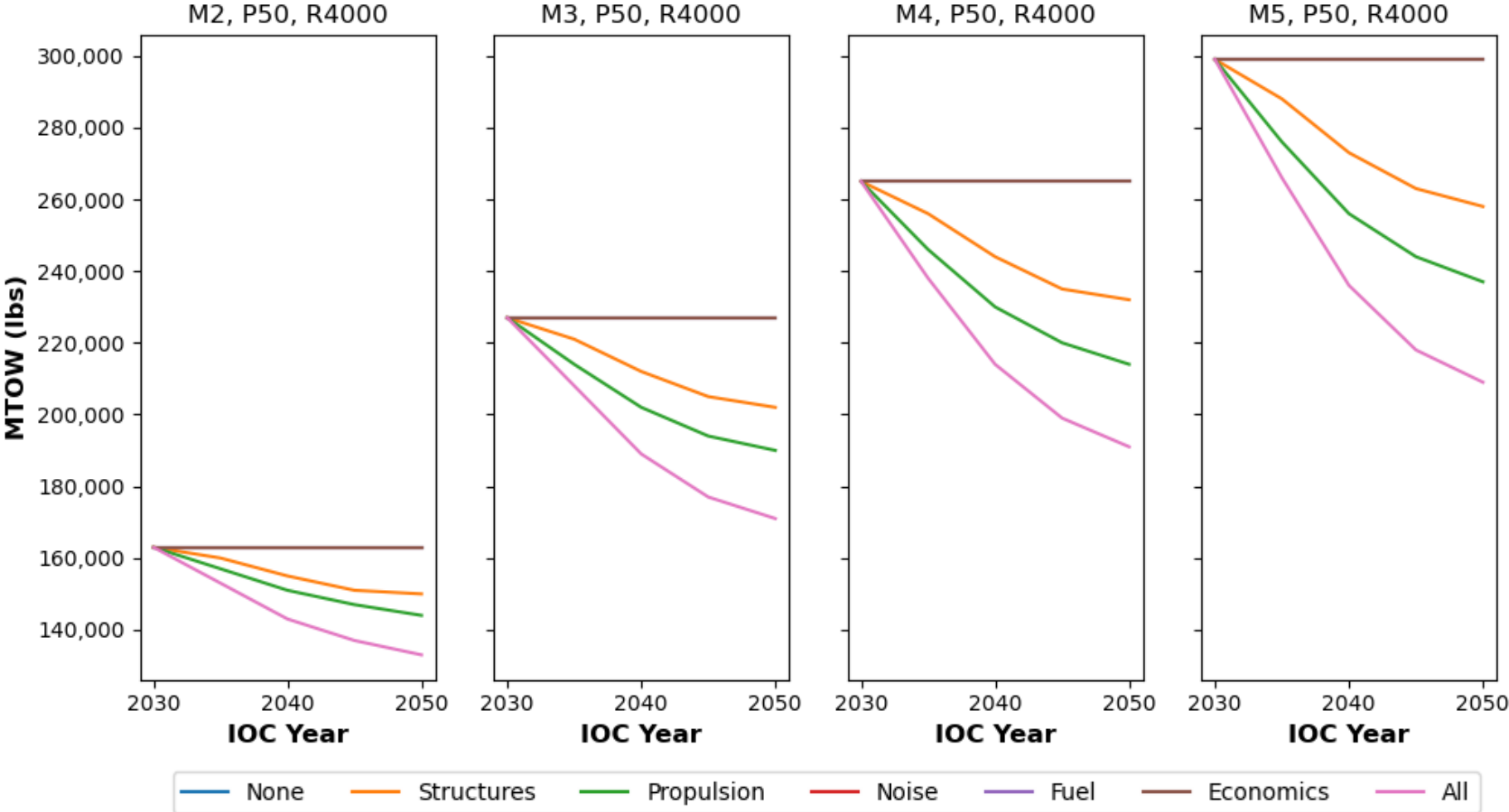
Market Capture | SAF

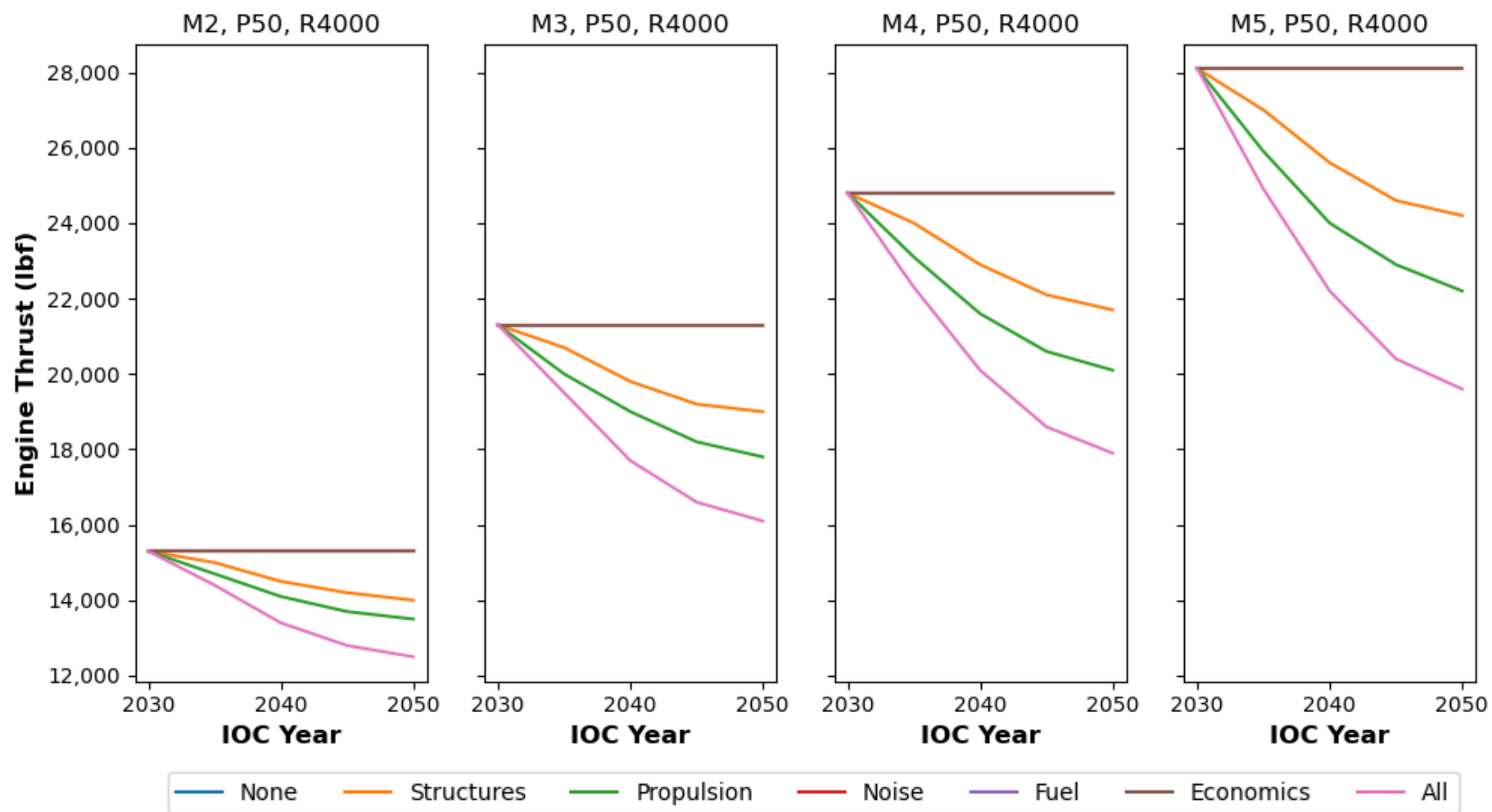


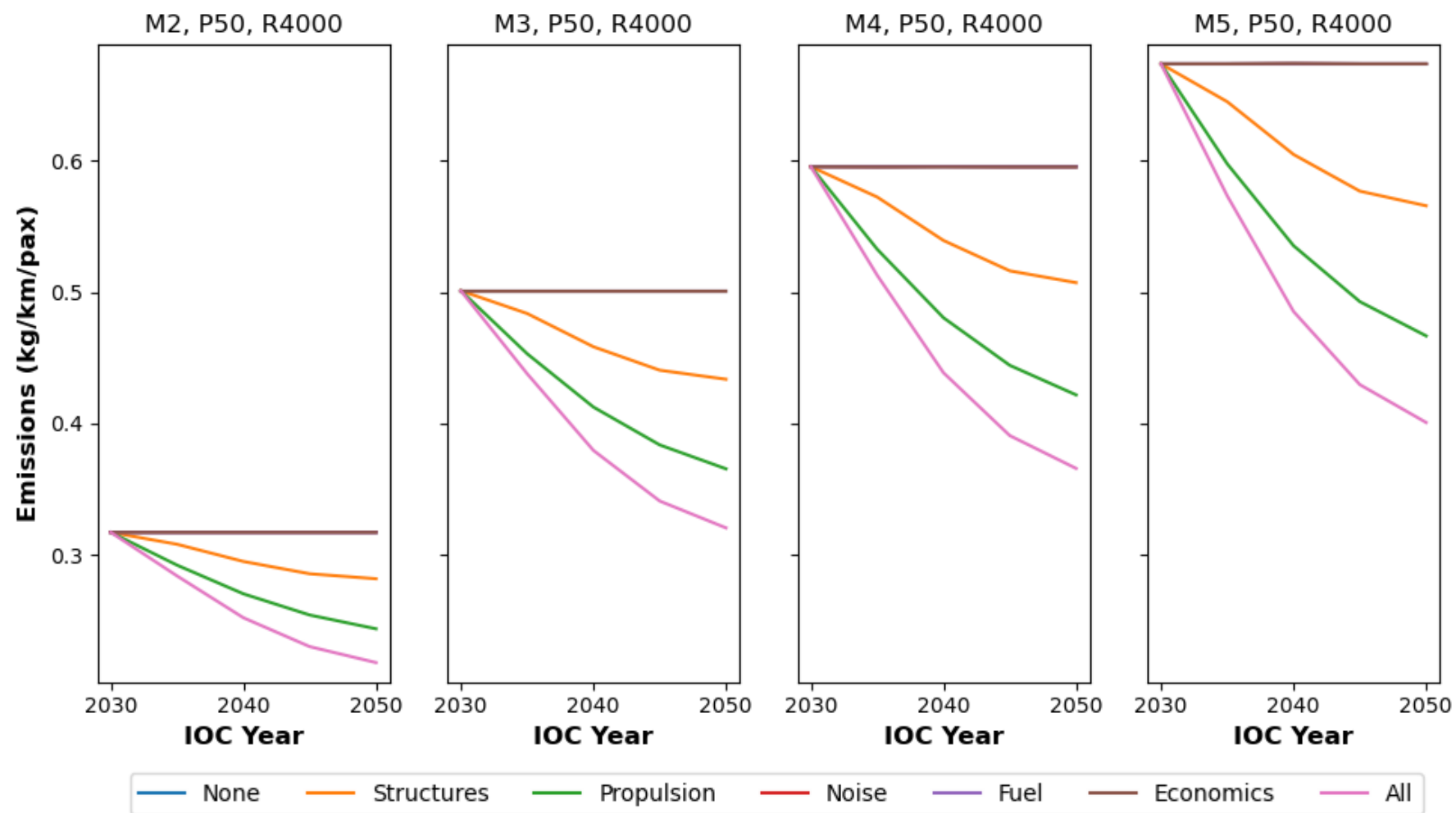


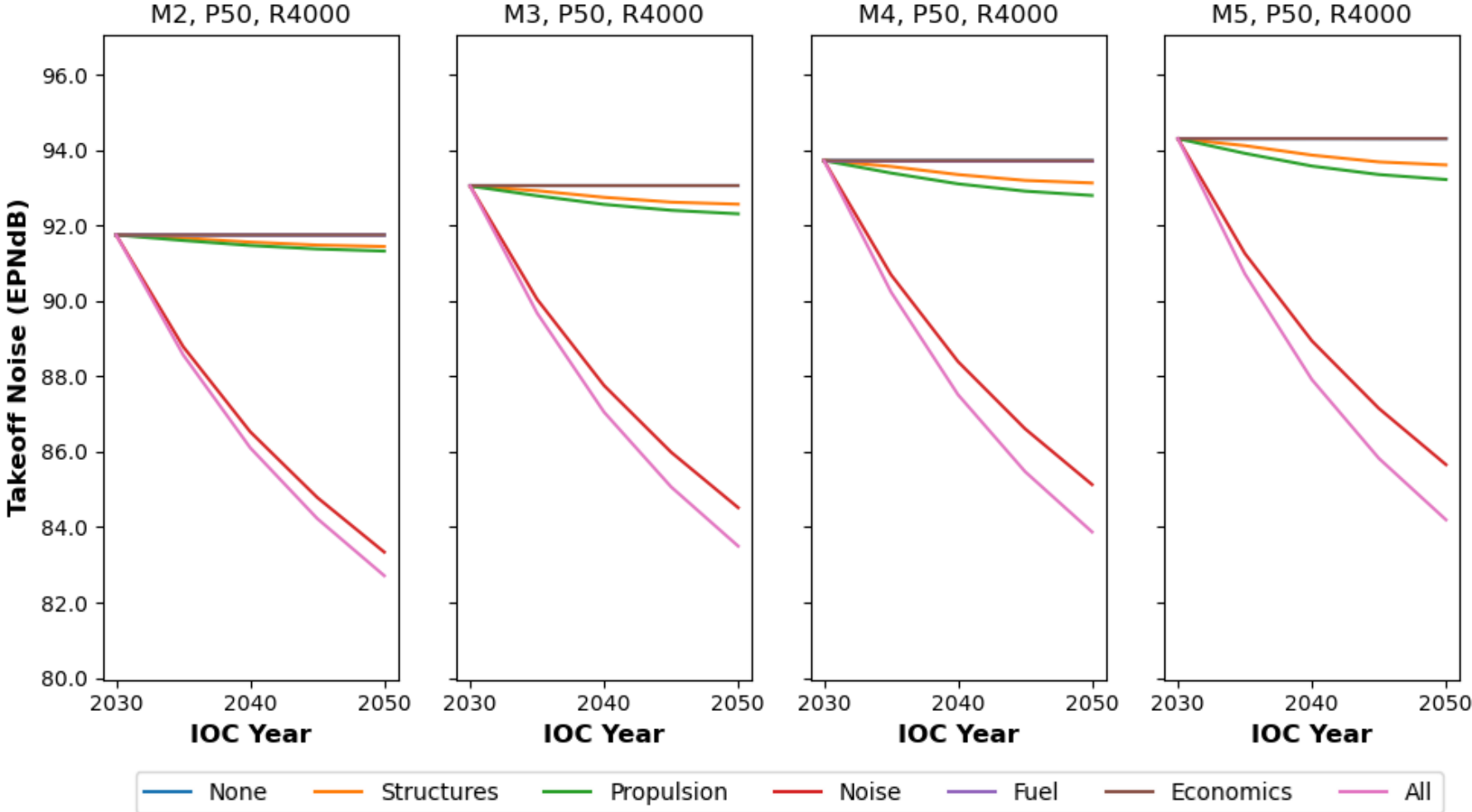






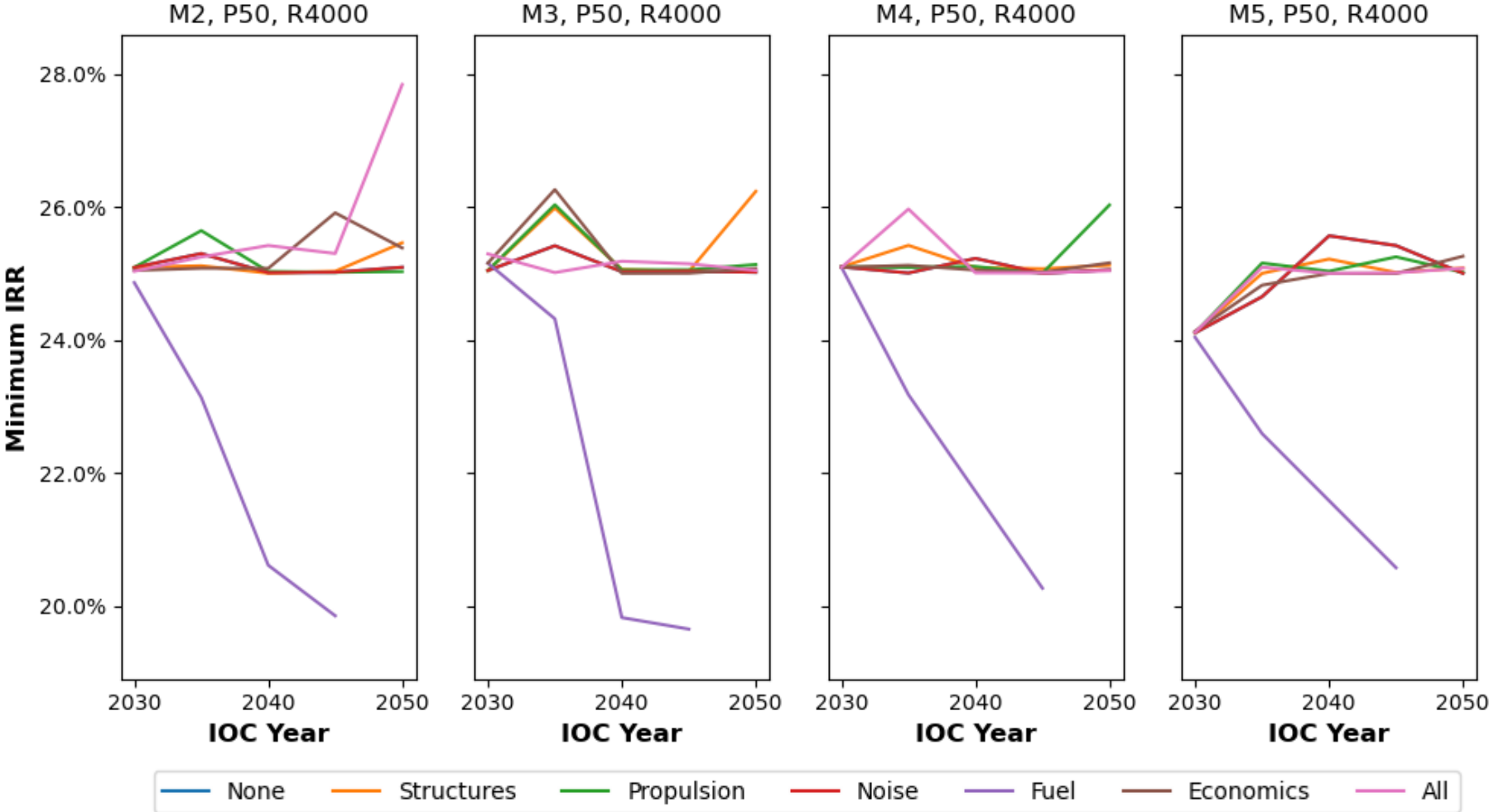




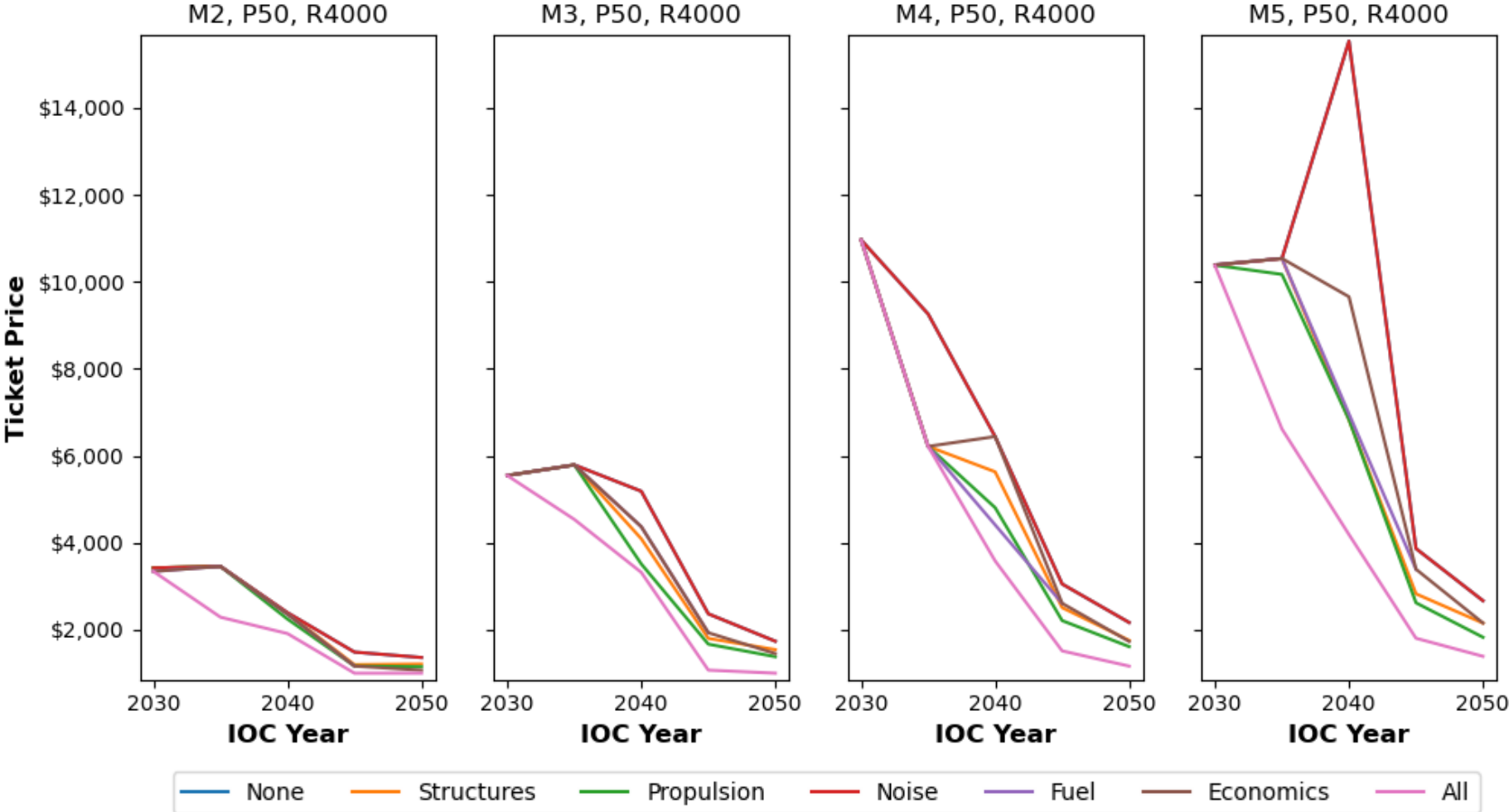




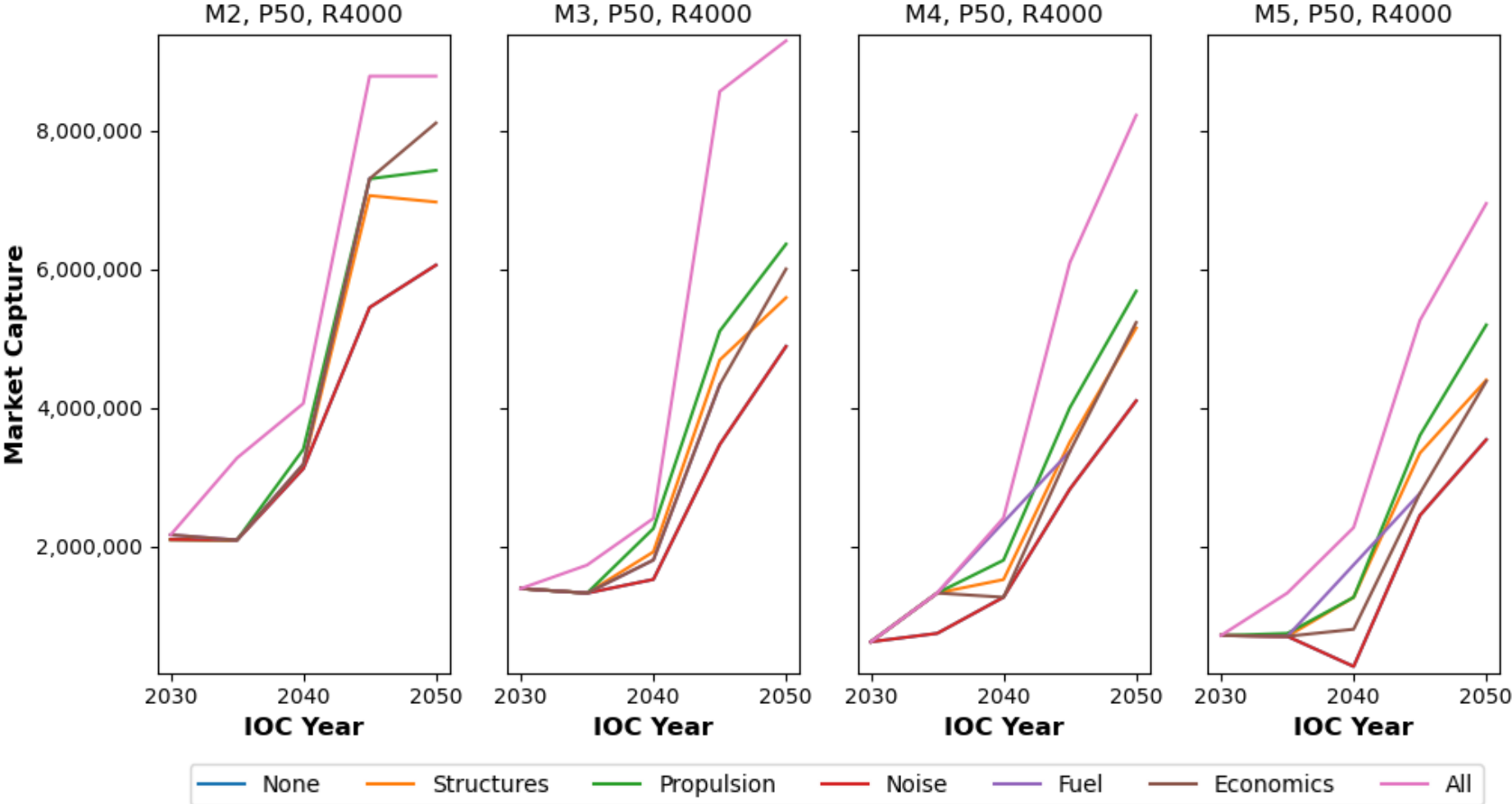
LNG



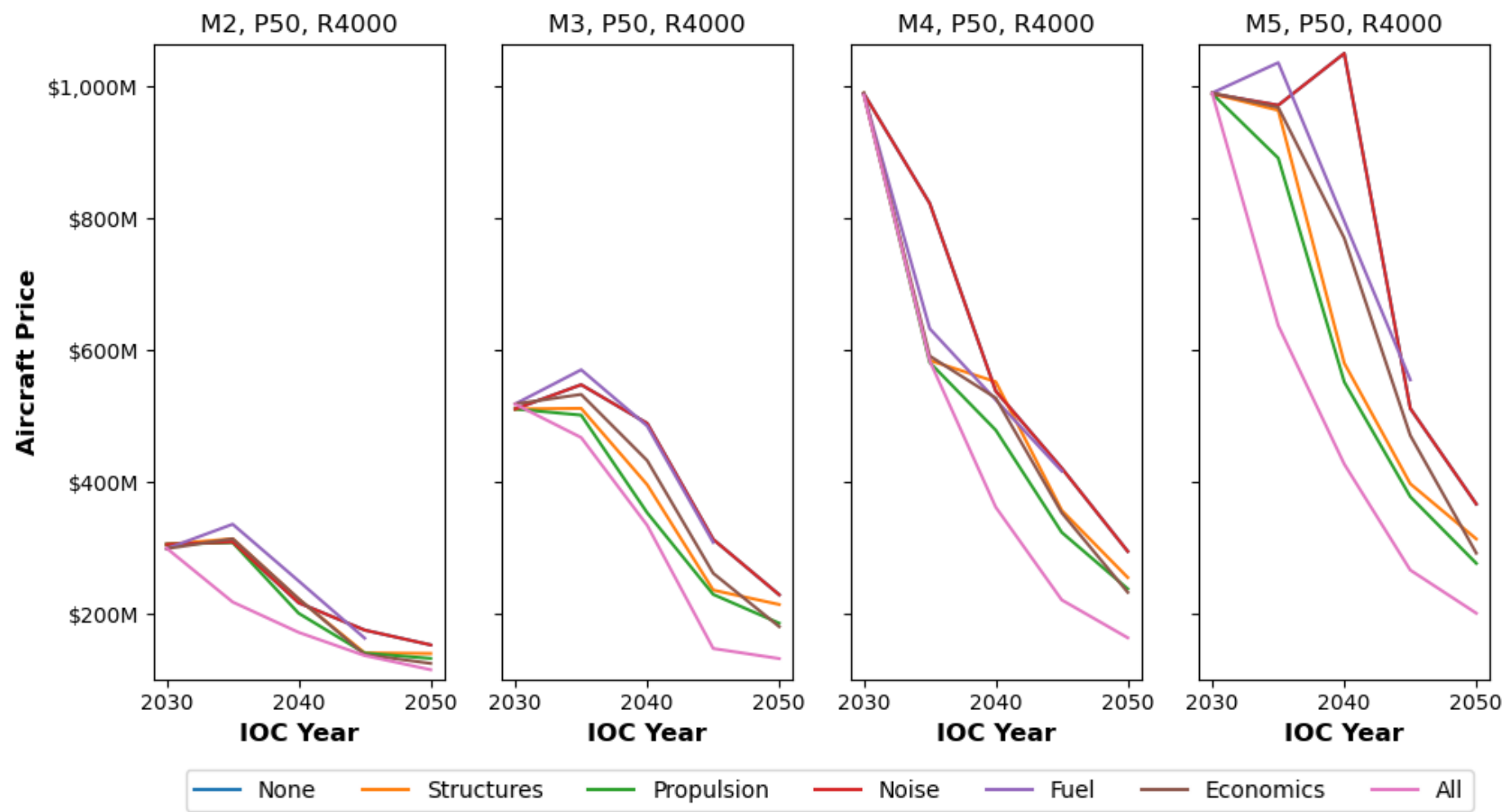
Ticket Price | LNG



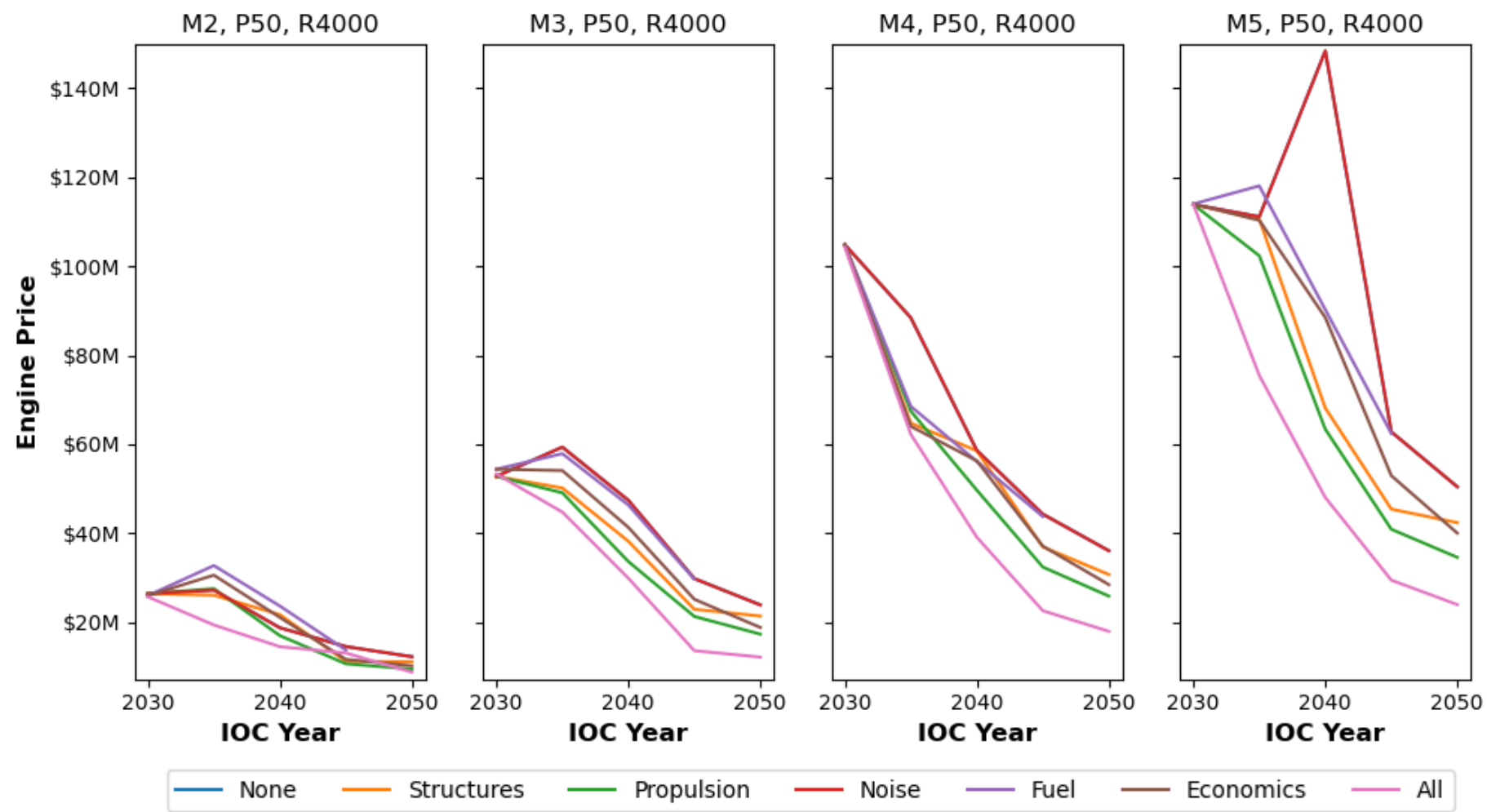
Market Capture | LNG



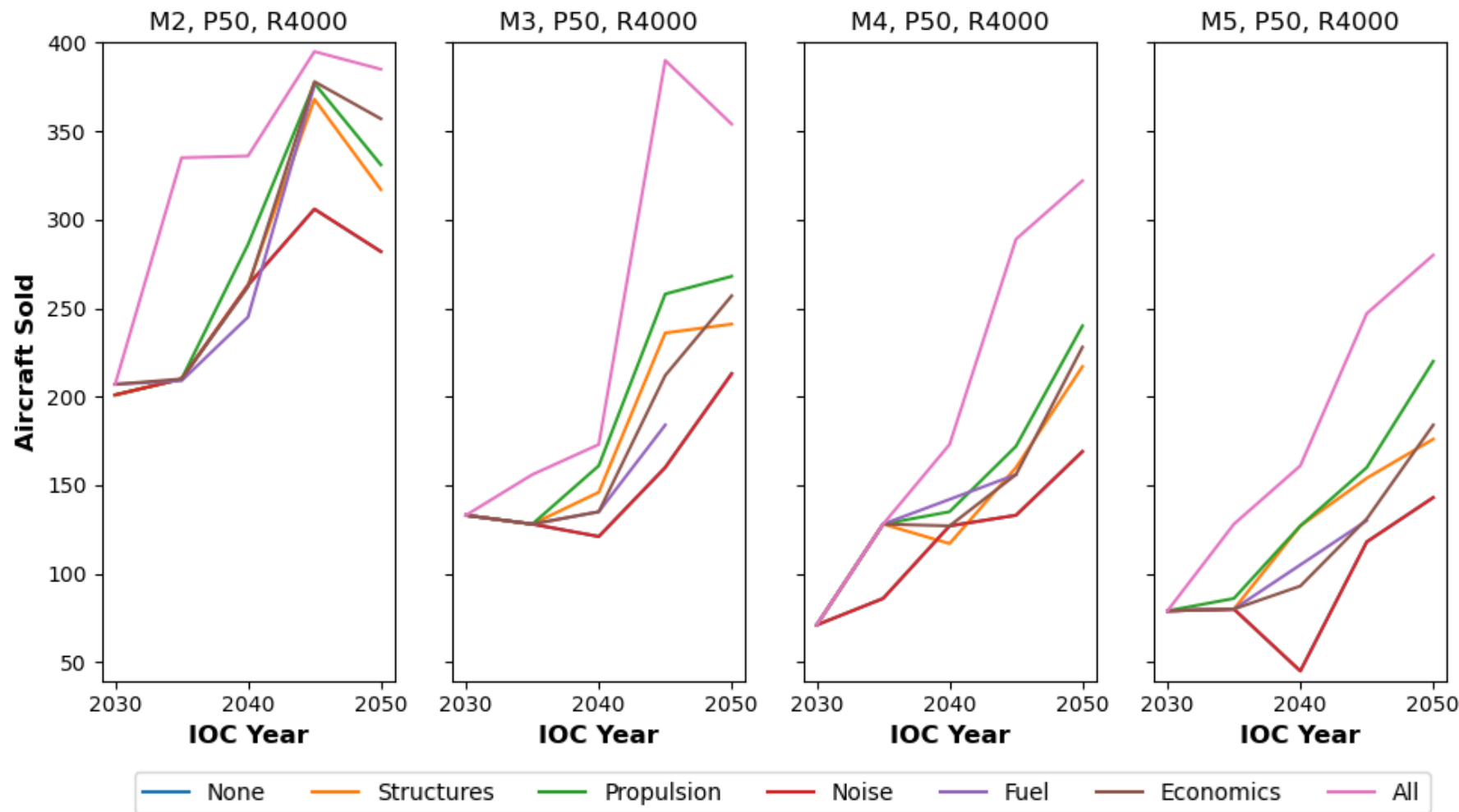
Aircraft Price | LNG

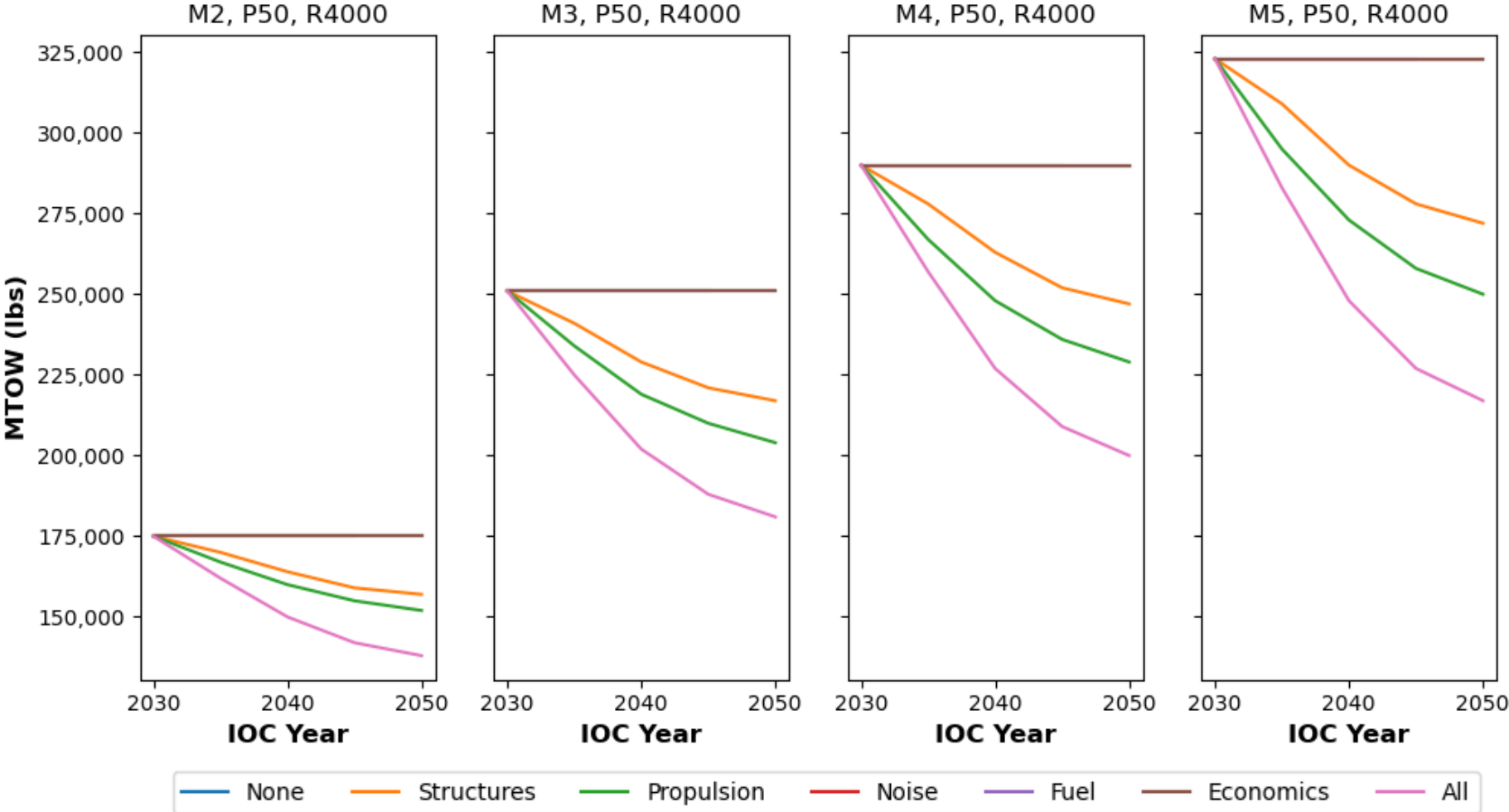


Engine Price | LNG

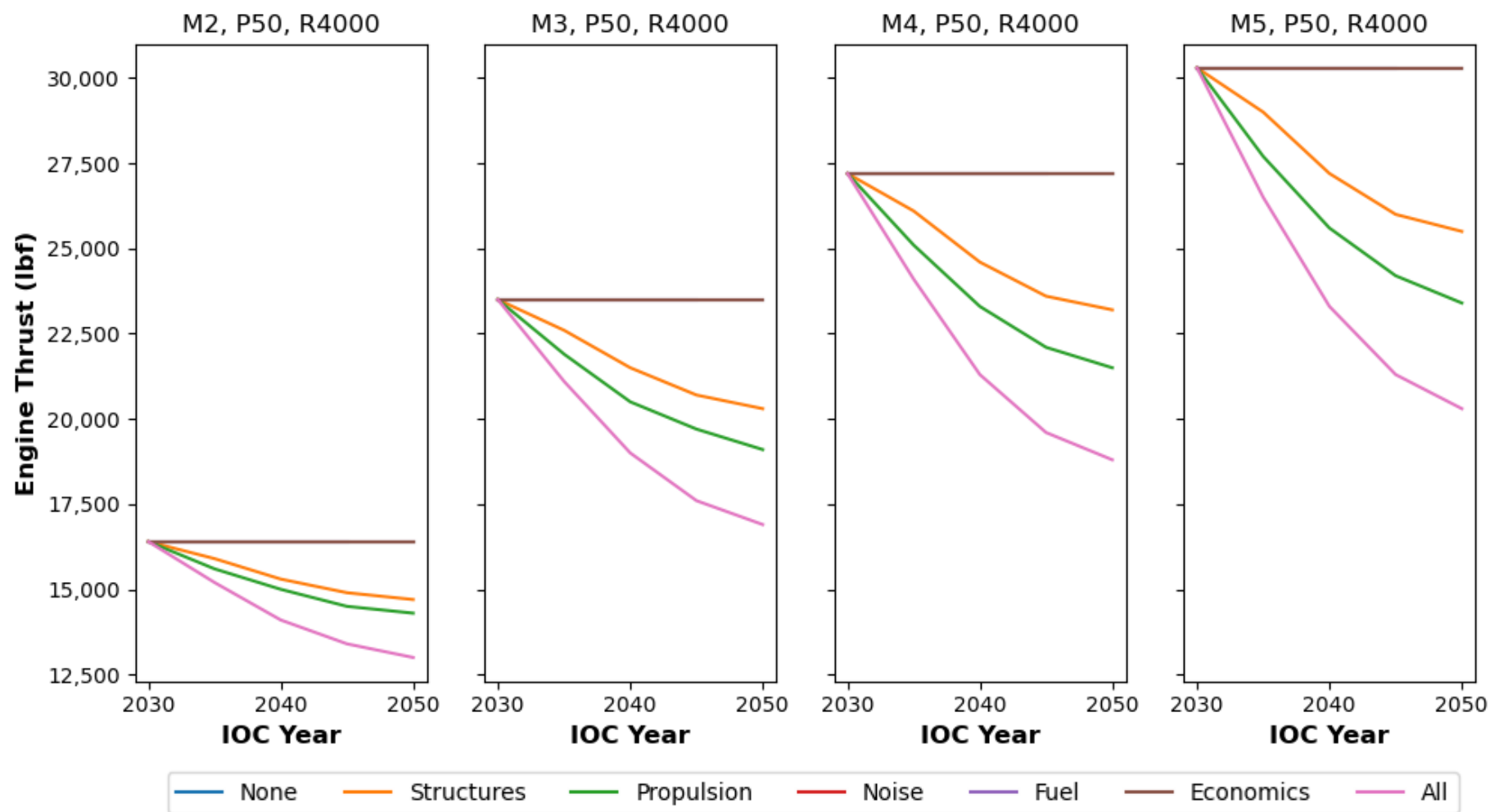


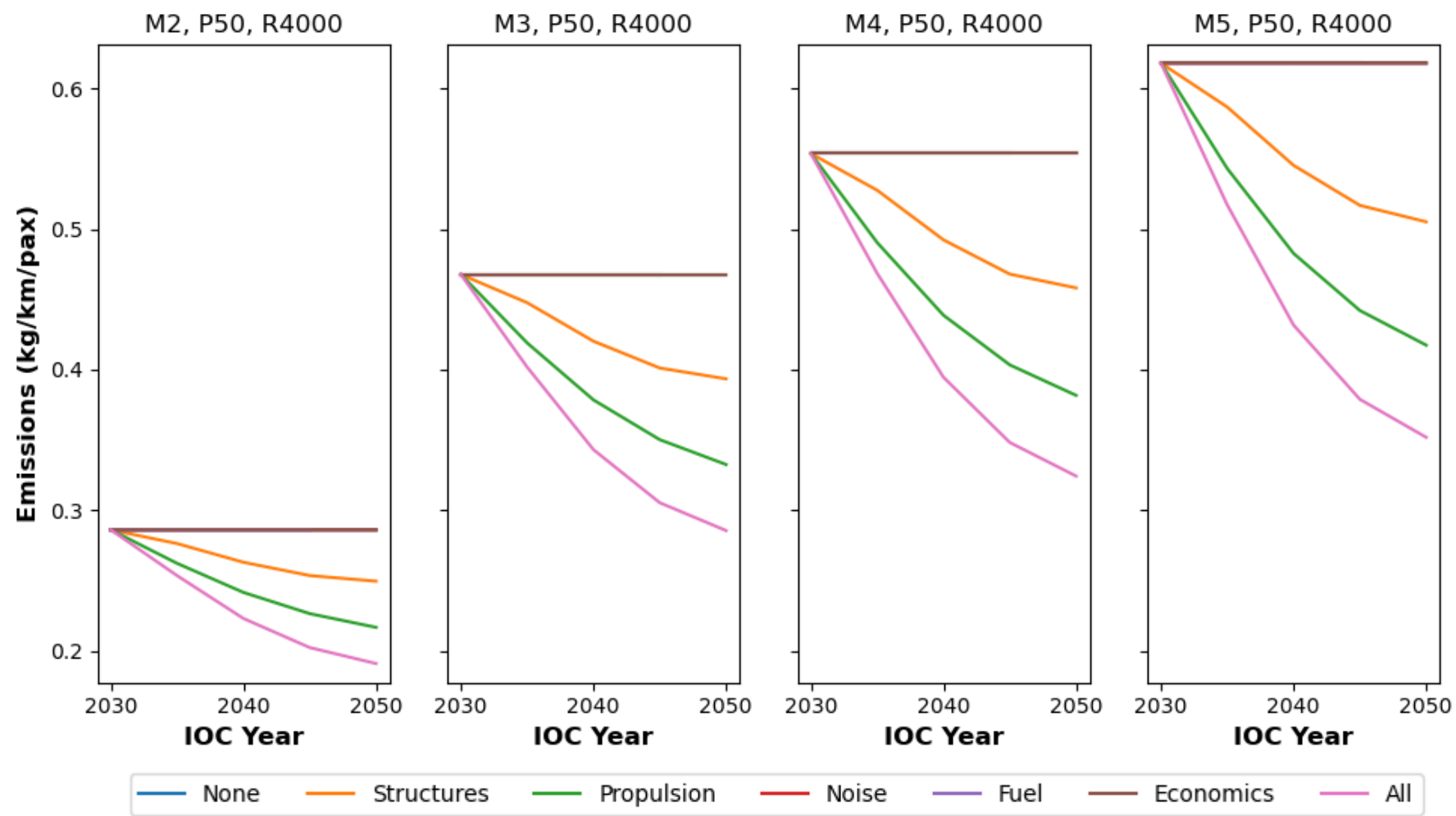
Aircraft Sold | LNG



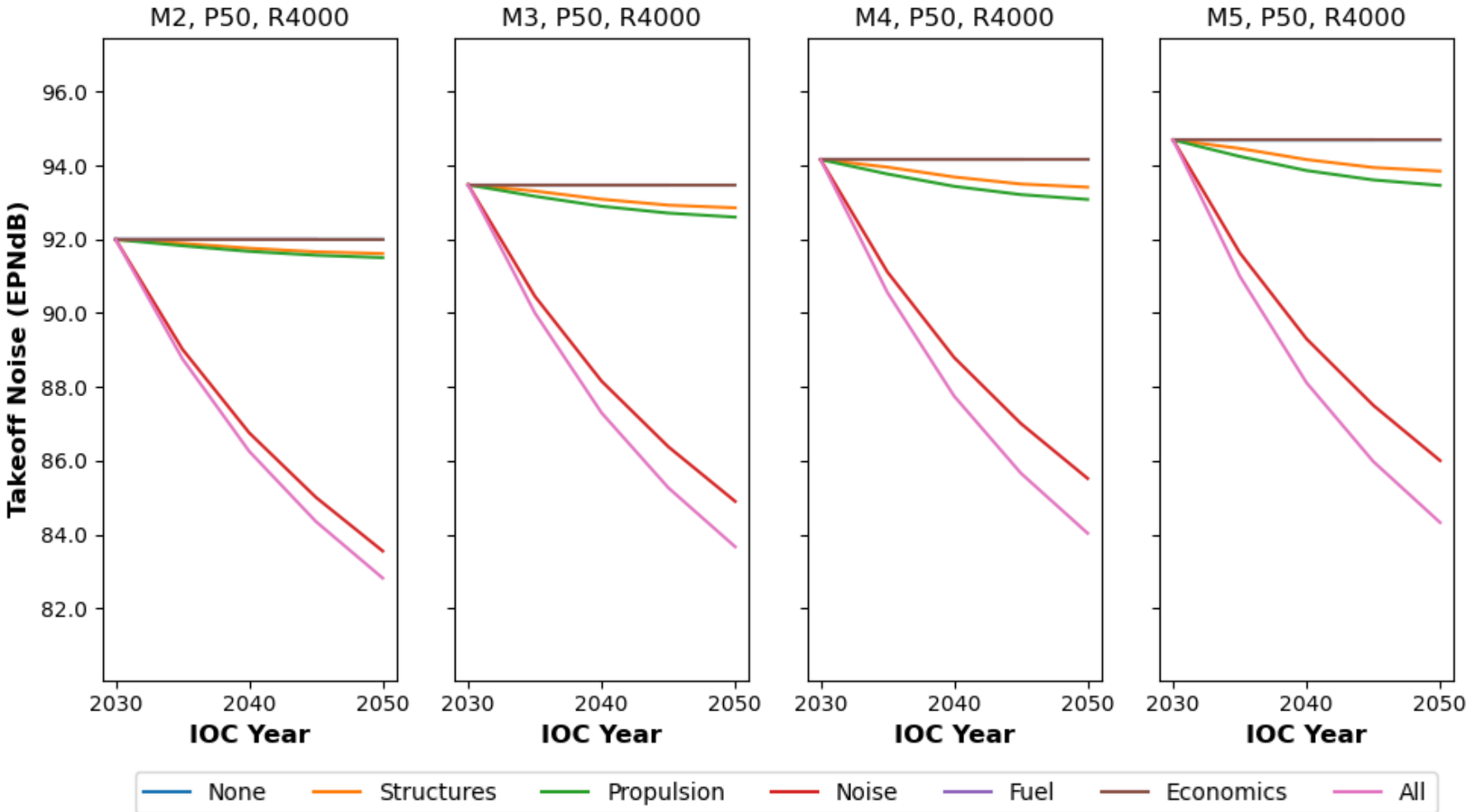


Engine Thrust | LNG



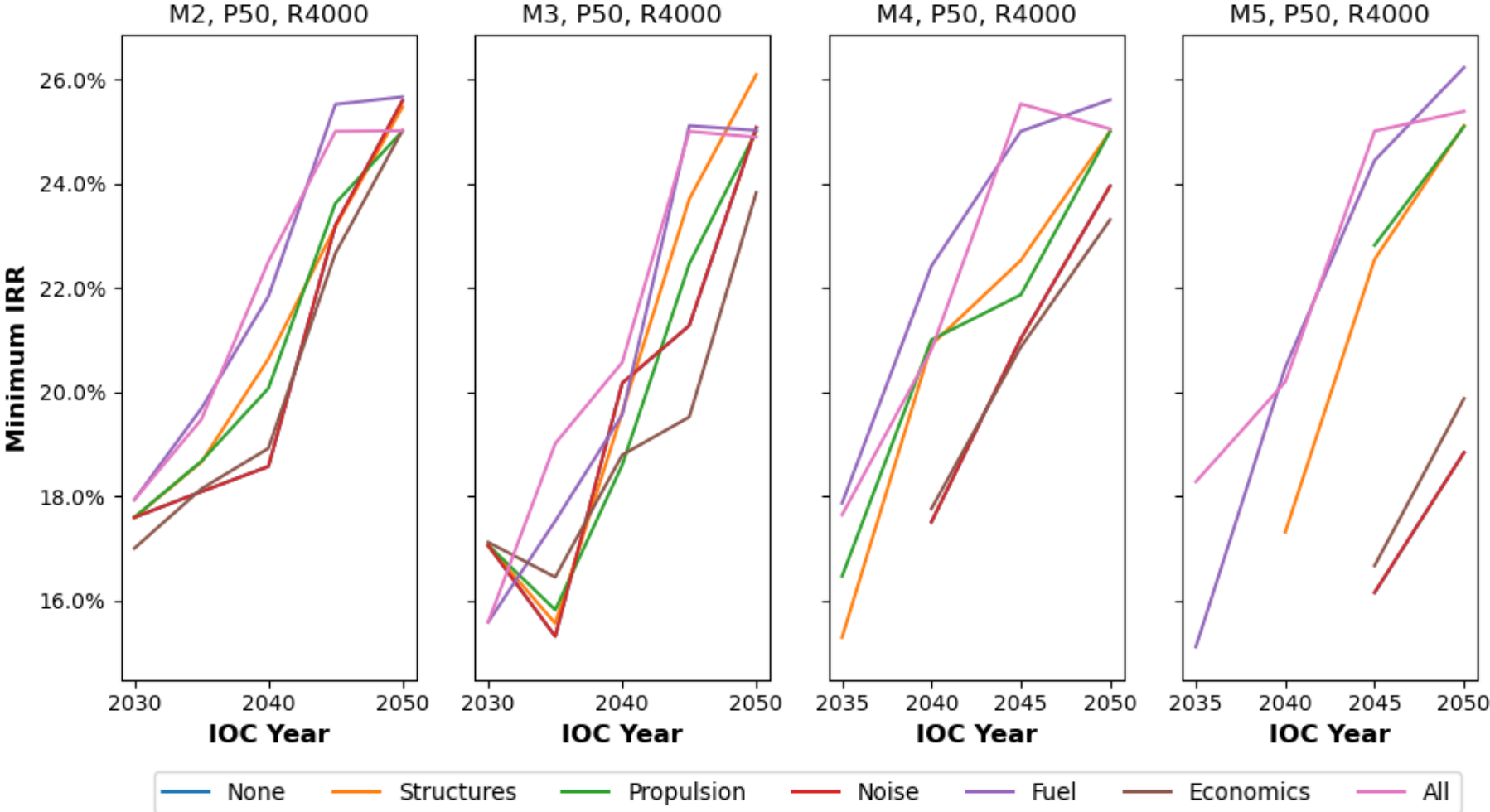


Takeoff Noise | LNG

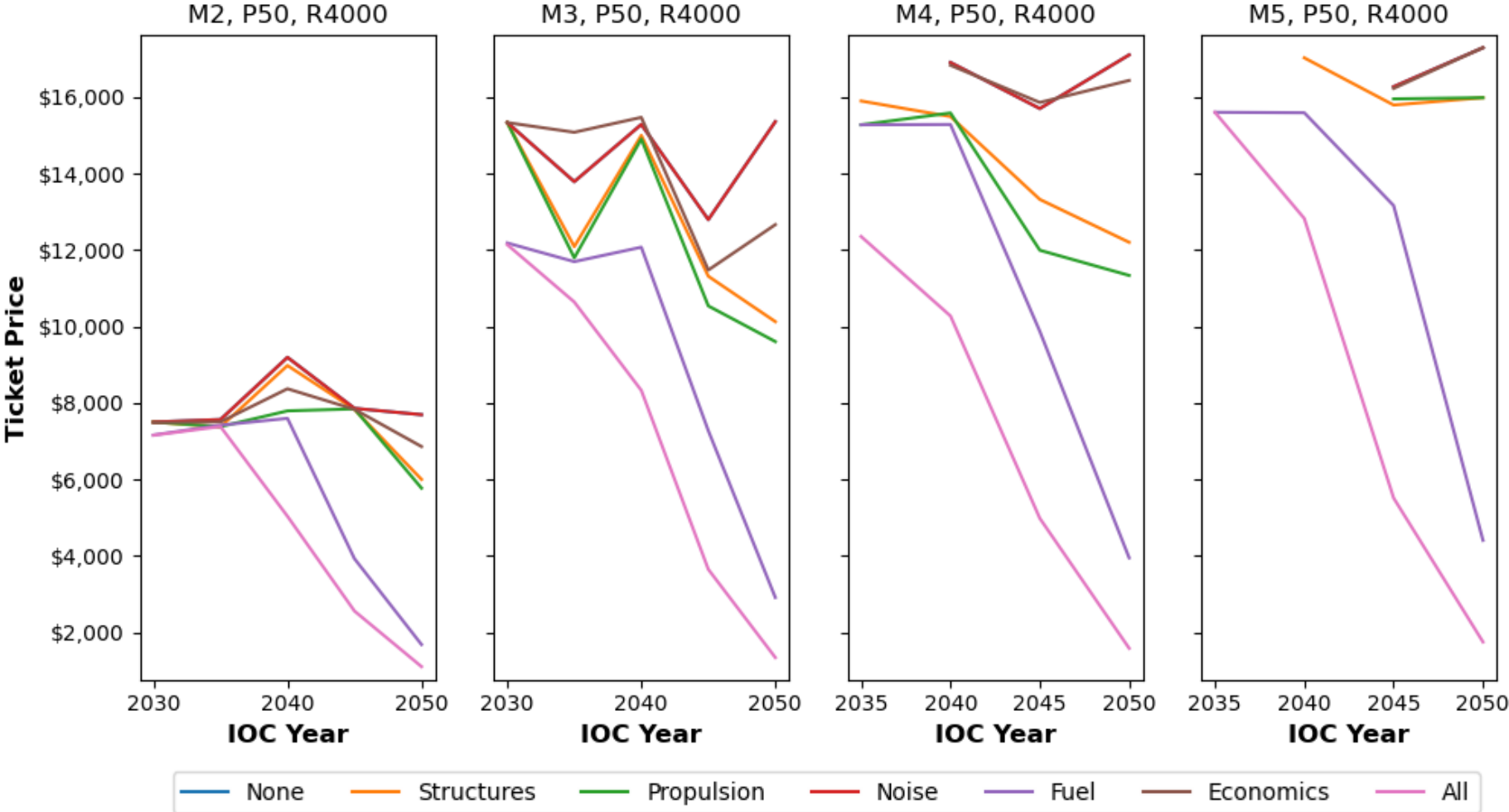




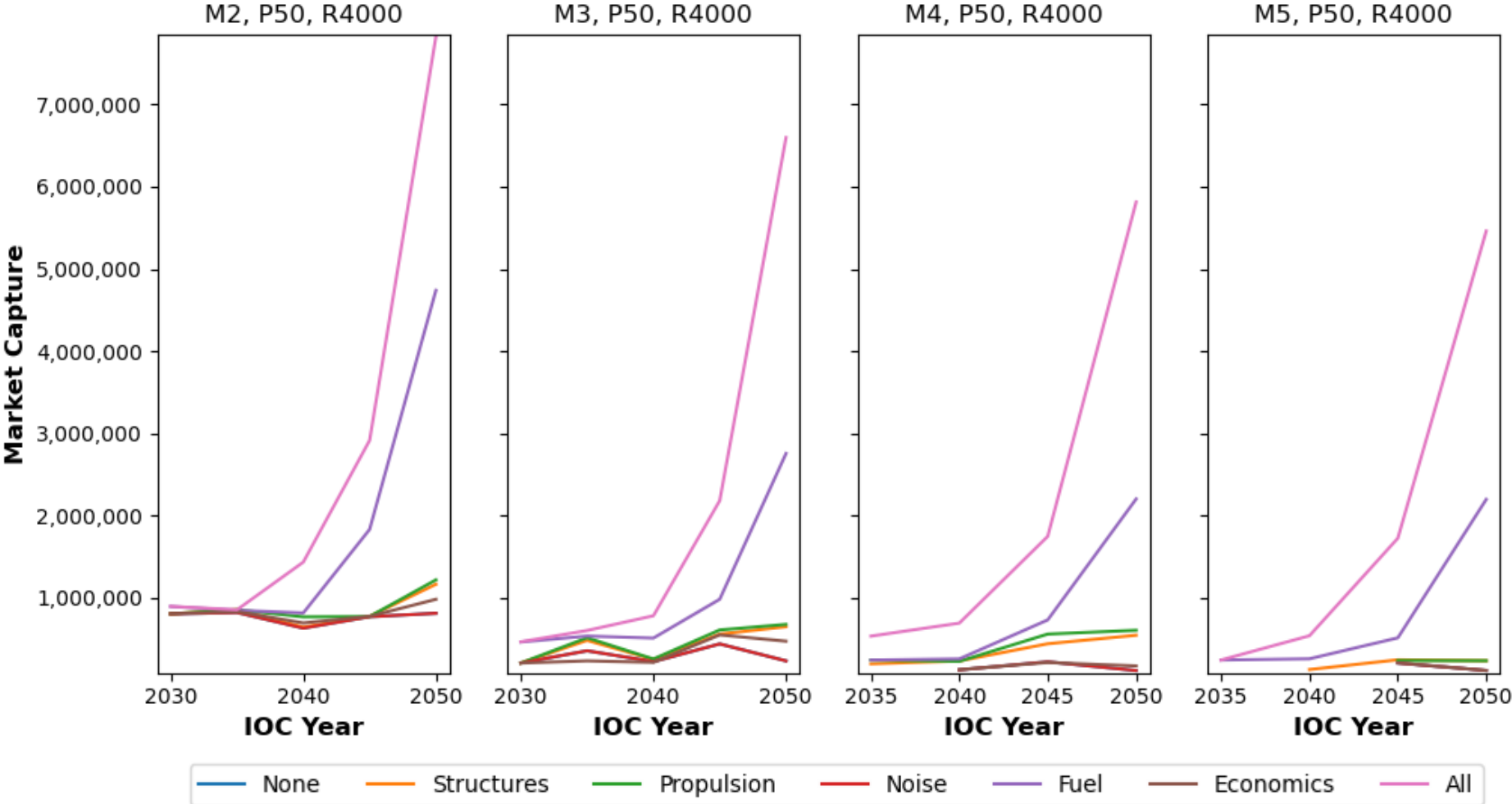
LH2



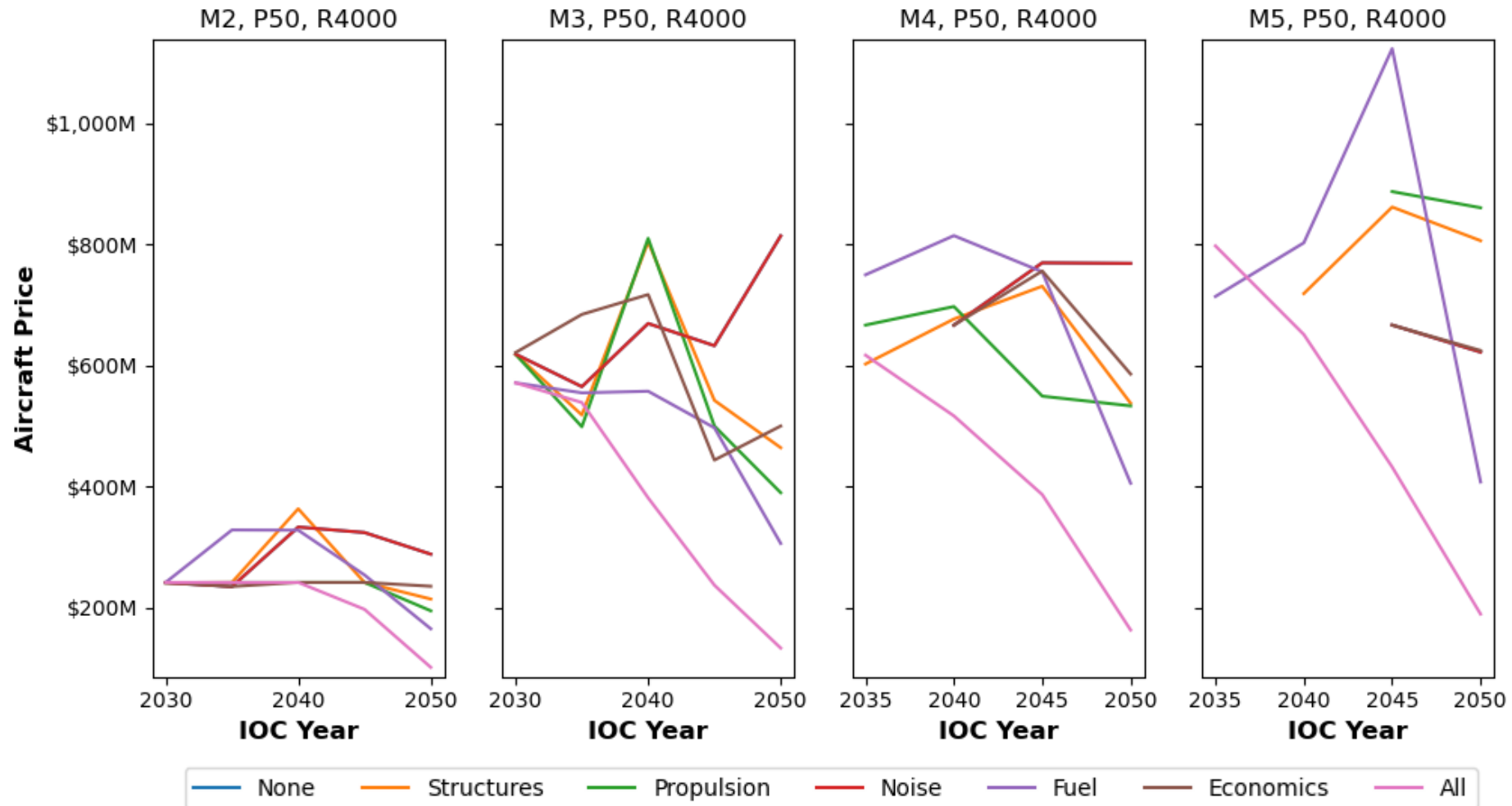
Ticket Price | LH2



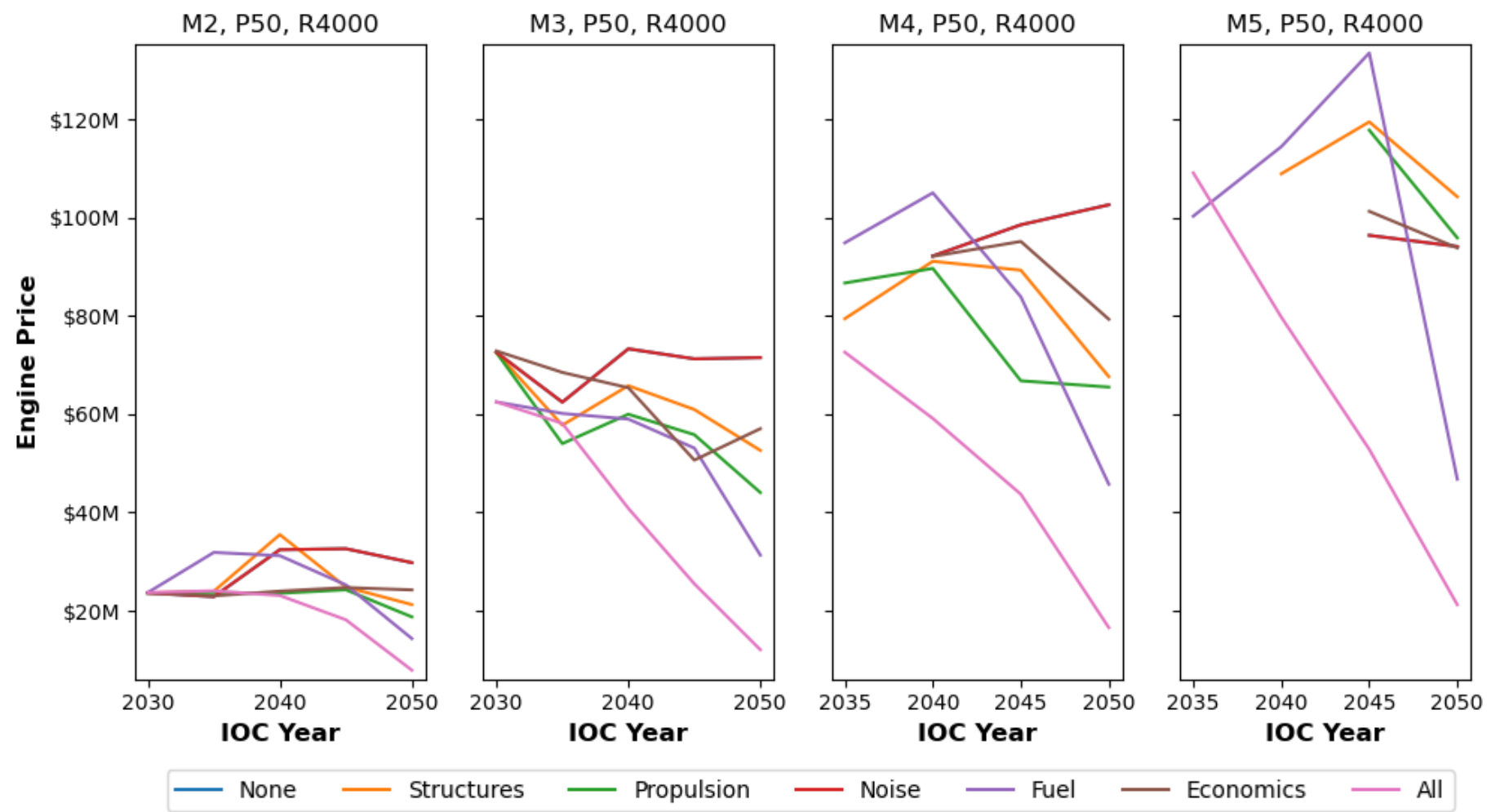
Market Capture | LH2



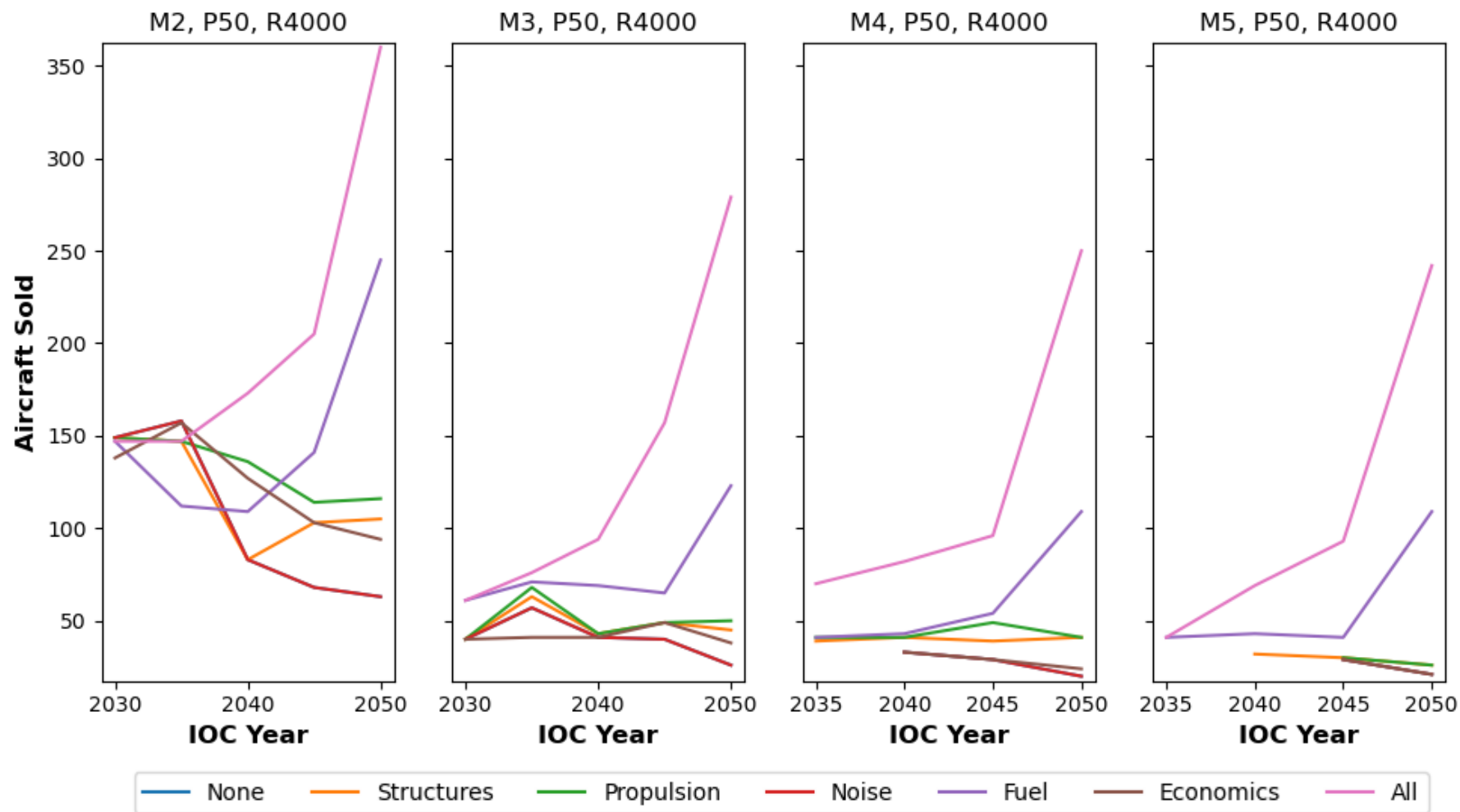
Aircraft Price | LH2

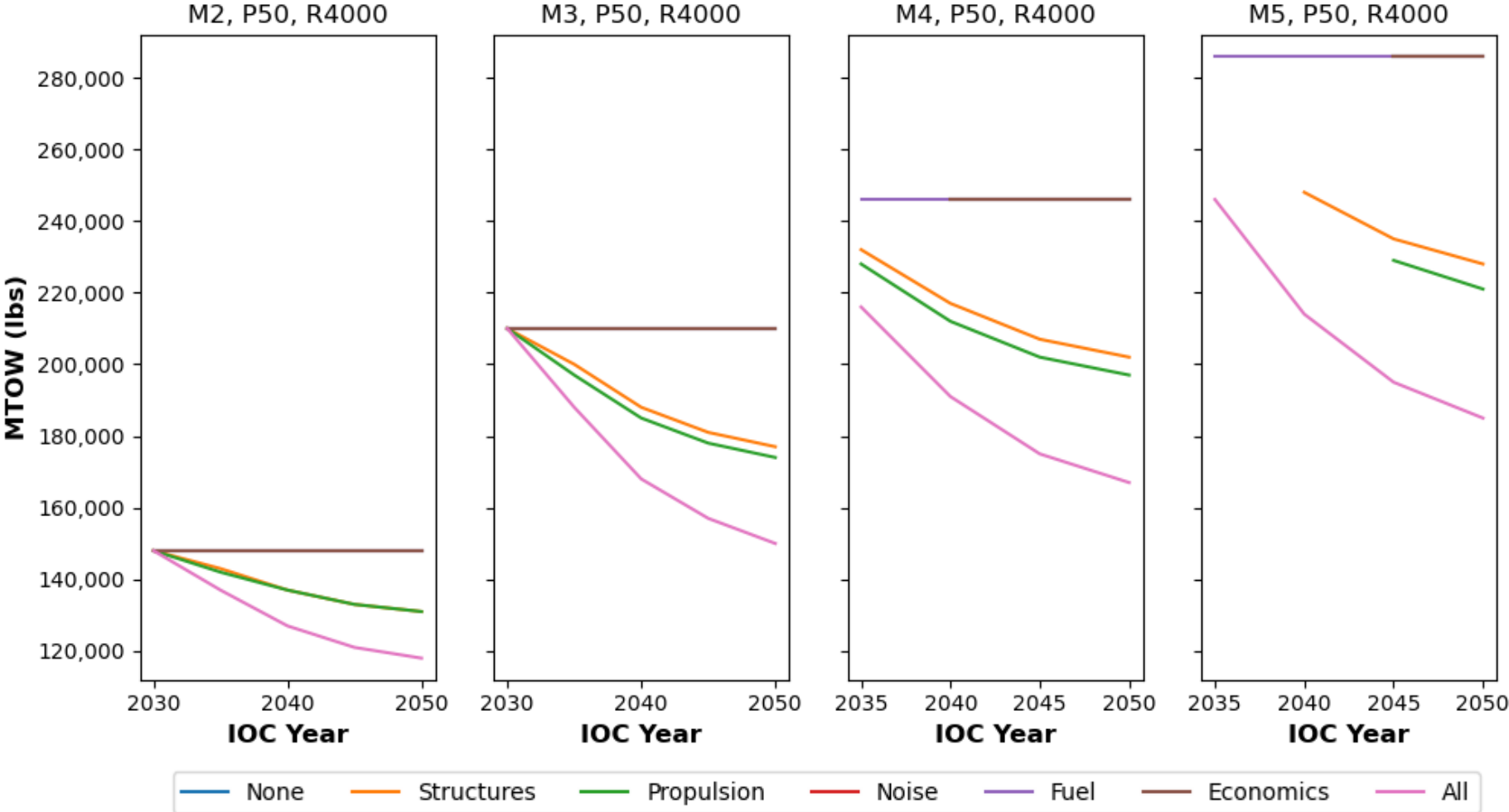


Engine Price | LH2

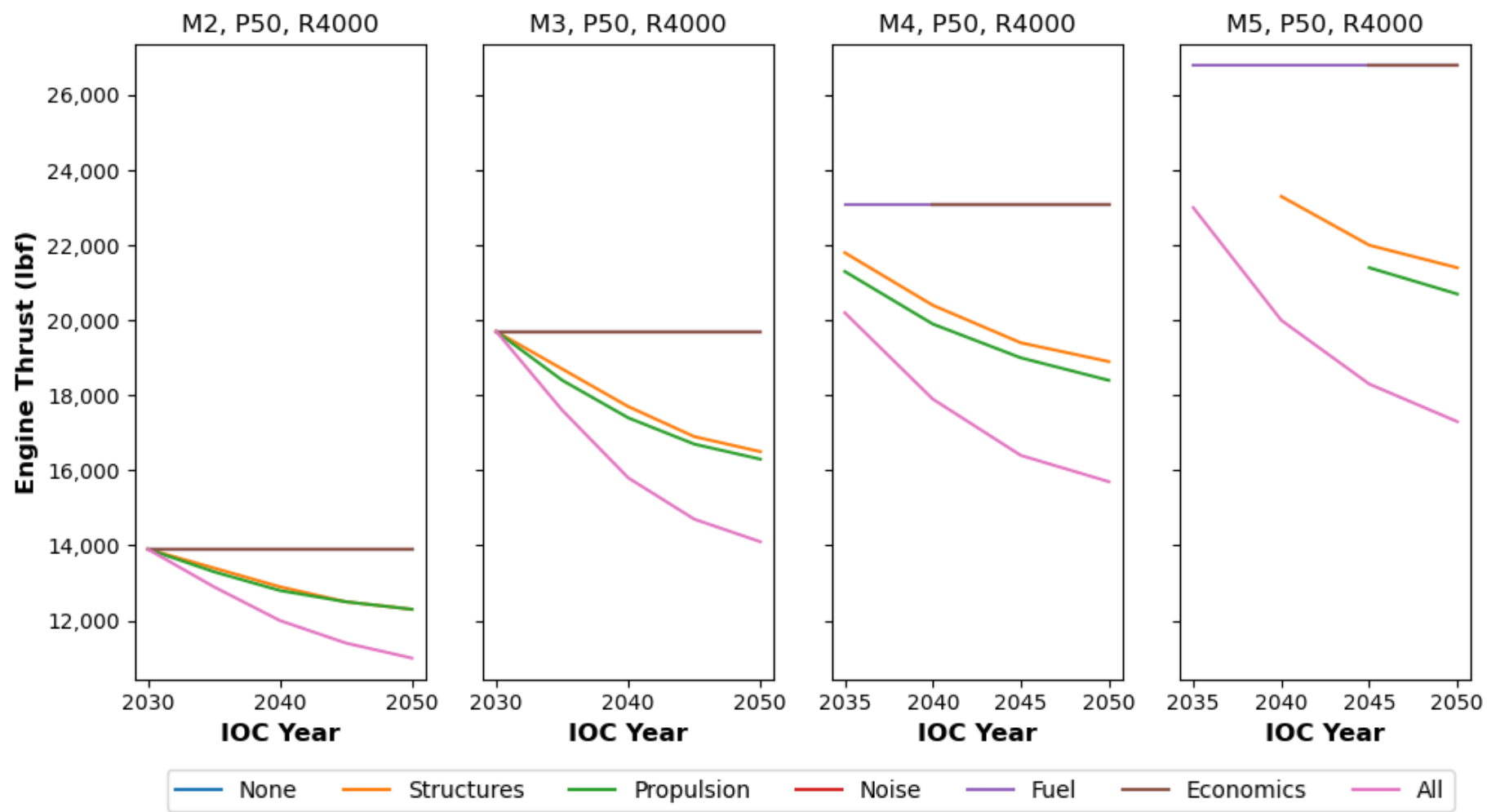


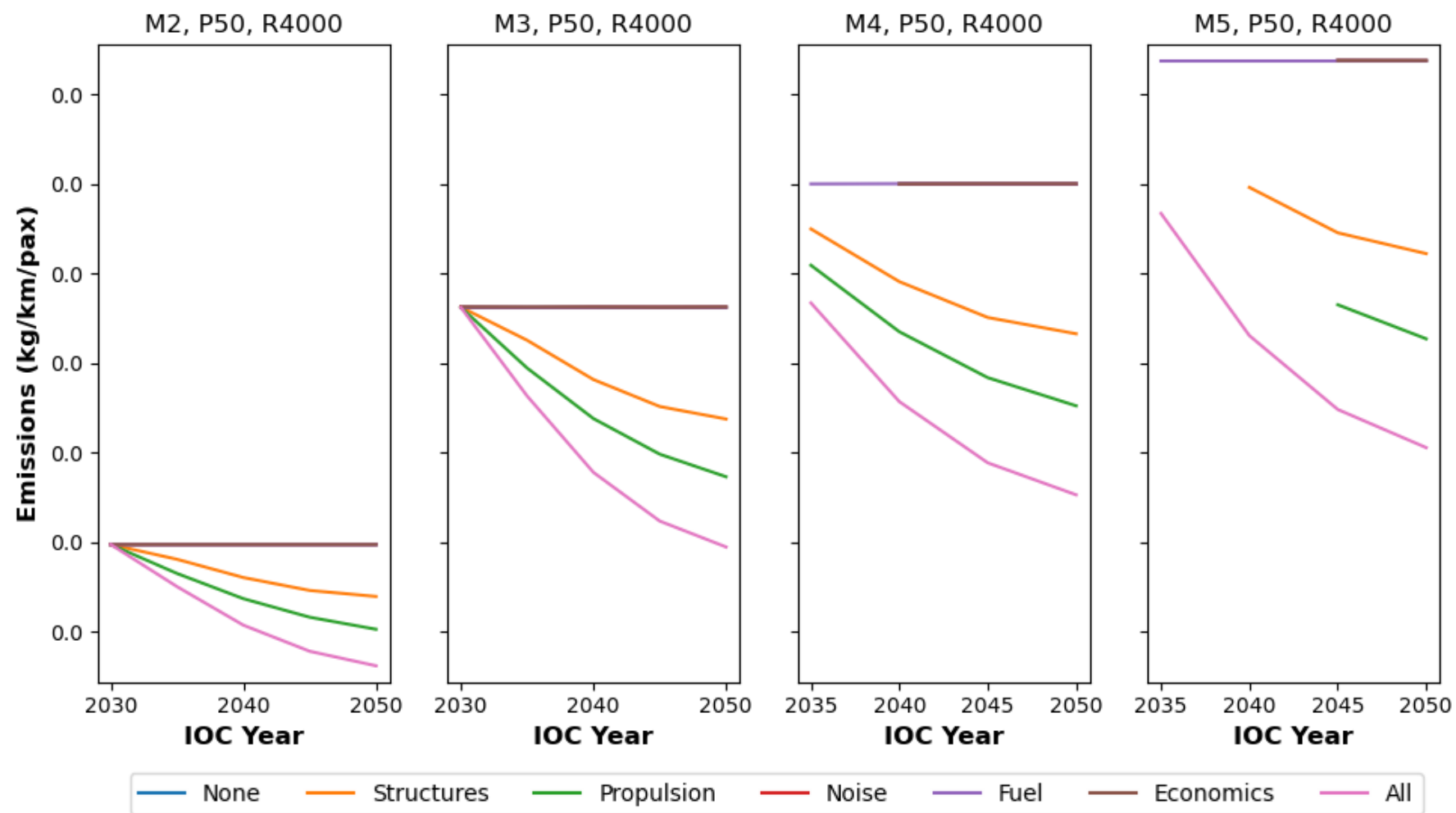
Aircraft Sold | LH2





Engine Thrust | LH2





Takeoff Noise | LH2

